**COMMONWEALTH OF KENTUCKY**
**BEFORE THE PUBLIC SERVICE COMMISSION**

In the Matter of:

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|---|---|---|
| ELECTRONIC APPLICATION OF EAST KENTUCKY POWER COOPERATIVE, INC. FOR 1) CERTIFICATES OF PUBLIC CONVENIENCE AND NECESSITY TO CONSTRUCT A NEW GENERATION RESOURCES; 2) FOR A SITE COMPATIBILITY CERTIFICATE RELATING TO THE SAME; 3) APPROVAL OF DEMAND SIDE MANAGEMENT TARIFFS; AND 4) OTHER GENERAL RELIEF | )<br>)<br>)<br>)<br>)<br>)<br>)<br>)<br>)<br>) | CASE NO. 2024-00370 |

# TESTIMONY OF MARIA ROUMPANI, PhD

## ON BEHALF OF JOINT INTERVENORS APPALACHIAN CITIZENS' LAW CENTER, KENTUCKIANS FOR THE COMMONWEALTH, AND MOUNTAIN ASSOCIATION

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Dated: February 14, 2025

**DIRECT TESTIMONY OF MARIA ROUMPANI, PHD**
**ON BEHALF OF JOINT INTERVENORS**
**BEFORE THE PUBLIC SERVICE COMMISSION OF KENTUCKY**

**Case No. 2024-00370**

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## I. INTRODUCTION

**Q. Please state your name and business address.**

A. My name is Maria Roumpani, and my business address is 2900 E. Broadway Blvd, Ste. 100 #780, Tucson, AZ 85716.

**Q. By whom are you employed, and in what capacity, for the purposes of this proceeding?**

A. I am a Founding Partner at Current Energy Group, a consulting group dedicated to providing tailored technical support and economic analysis for today's energy and climate challenges. I am providing comments and testimony on behalf of the Joint Intervenors, comprised of Appalachian Citizens' Law Center, Kentuckians for the Commonwealth, and Mountain Association.

## II. BACKGROUND AND QUALIFICATIONS

**Q. Please summarize your educational background and professional qualifications.**

A. I specialize in the economic and technical analysis of grid planning and operations issues. I have conducted analysis and submitted expert testimony or comments on integrated resource planning, plant economics, unit commitment practices, and power cost issues before state utility regulators in Arizona, Colorado, Kentucky, Michigan, Minnesota, Nevada, North Carolina, Oregon, South Carolina, Utah, Virginia, and Washington.

Prior to co-founding Current Energy Group in 2024, I was the Technical Director at Strategen. While at Strategen, I led economic and technical grid modeling engagements, including capacity expansion, production cost, and energy storage dispatch modeling. My clients included government entities and state bodies, including the Oregon Public Utility Commission, the Maryland Office of People's Counsel, and the South Carolina Office of

Regulatory Staff; non-governmental organizations; trade associations; as well as large energy buyers.

Before joining Strategen in 2018, I contributed to the development of analytical tools used in energy impact assessment studies. I have a Ph.D. from the Management Science and Engineering Department at Stanford University and a Master of Science in Electrical and Computer Engineering from the National Technical University of Athens, Greece. My full resume is attached to this testimony as Exhibit MR-1 – Maria Roumpani Résumé.

**Q. Have you previously testified before the Kentucky Public Service Commission (“Commission”)?**

A. No, I have not.

**Q. Have you ever testified before any other state regulatory body?**

A. I have testified before state utility regulators in Colorado, Michigan, Nevada, North Carolina, Oregon, and South Carolina.

## III. PURPOSE OF TESTIMONY

**Q. What is the purpose of your testimony?**

A. My testimony addresses East Kentucky Power Cooperative’s (“EKPC”) application for approval of a Demand Side Management (“DSM”) plan consisting of four new programs, three existing programs with expanded incentives, and three existing programs without proposed changes. My testimony addresses (a) the development of the DSM portfolio, and its consistency with the 2024 Potential Study, as well as with EKPC’s supply-side resource planning, (b) each of the proposed programs, exploring whether those are useful, affordable, and available to all customers, (c) the 2024 Potential Study, including its findings and any shortcomings in its development. I conclude with a set of recommendations for how EKPC could enhance its DSM plan and achieve more energy and cost savings for its owner-members and their customers.

**Q. Please summarize your findings.**

A. The EKPC DSM plan will result in energy and cost savings. However, it is arbitrarily limited based on historical incentive and budget levels, instead of being optimized to capture all available savings for EKPC, its owner-members, and their customers. My findings are:

- EKPC's plan targets savings that are only a small fraction of what the EKPC 2024 Potential Study has identified as realistically achievable.
- EKPC's demand-side resources are significantly more economic than the proposed supply-side additions and should have been further expanded to reduce or delay the need for higher-cost alternatives.
- EKPC's Demand Response ("DR") offerings are very limited and not designed to address EKPC's winter capacity need.
- EKPC's Energy Efficiency ("EE") offerings miss out on potential savings across all end-uses.
- EKPC's EE programs have high utility cost test ("UCT") and total resource cost test ("TRC") scores, providing room for higher incentives that can increase participation.
- The 2024 Potential Study understates the realistically achievable potential ("RAP") by arbitrarily limiting incentives to historical levels.

**Q. Please summarize your recommendations for the Kentucky Public Service Commission.**

A. I recommend that the Commission:

- Approve the proposed DSM Plan for program years 2025, 2026, and 2027, with immediate modifications:
    - Extend the plan's budget to at least $11.4 million (reflecting the High scenario developed in the 2024 Potential Study), ensuring that programs are available to more customers.
    - Modify the Demand Load Control ("DLC") Bring Your Own Thermostat ("BYOT") program to allow for winter peak reduction.
    - Offer the DLC and Back-up generator programs to Commercial & Industrial ("C&I") customers.
    - Increase the incentives provided for all residential programs, especially those of shell programs.
- Order EKPC to develop, within six months of a final order in this proceeding, an updated DSM Plan proposal that will aggressively pursue all realistically achievable DSM programs as identified in the 2024 Potential Study.
    - The proposal should pursue at least the RAP savings as projected in the 2024 Potential Study, namely 400,000 MWh of energy efficiency and winter peak demand reductions of 173 MW by 2030.[1]
    - Explore additional programs that at minimum include:
        - Residential and Commercial Energy Assessments and programs targeting behavioral changes.
        - Additional Residential programs targeting inefficient electric heating, and water heating equipment.
        - Programs tailored for manufactured housing.
        - New Commercial programs targeting savings from heating, motors, and refrigeration uses, all of which can also deliver winter demand savings.
        - Non-residential EV charging plans.
    - Explore financing opportunities and new program designs in line with national best practices to overcome persistent barriers to participation, e.g., Pay-As-You-Save Program ("PAYS®") model, also referred to as on-bill financing ("OBF") or Inclusive Utility Investment ("IUI") programs, to overcome high upfront cost barriers.

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[1] Note that Table 2, below, shows the basis for these energy and demand targets.

  - Evaluate the impact of increasing incentives for programs including, at minimum, the following programs:
    - DLC;
    - Commercial Advanced Lighting;
    - All residential heating, ventilation, and air conditioning ("HVAC") equipment and shell programs.

- Order EKPC to provide, within twelve months of a final order in this proceeding, an updated Potential Study or other serious analysis correcting for the flaws and shortcomings identified here to provide more accurate estimates of cost-effective, achievable potential. The updated analysis should include at least the following adjustments:
  - Determination of optimal incentives that aim to maximize energy and cost savings, without over-relying on unjustified limits on incentive and/or spending levels.
  - The assessment of the potential of distributed solar and energy storage resources.
  - The assessment of emerging technologies, including but not limited to bidirectional charging, and the types of technologies and program delivery mechanisms in the Exhibits MR-2, MR-3, MR-4, MR-5.
  - Together with the Potential Study, EKPC should provide a third-party process evaluation and feasibility study for implementing Time-of-Use ("TOU") and Critical Peak Pricing ("CPP") rates across its member utilities.

- Order EKPC to propose, by no later than Jan. 2027, an updated DSM Plan that will utilize and observe the updated potential study to pursue re-assessed achievable programs and include additional programs and measures recommended. That updated DSM Plan should also propose guidelines for the stakeholder collaborative process as well as EKPC's (and owner-members') in-house evaluation of the Potential Study findings in the development of the proposed DSM plan. Guidelines should ensure a transparent process and outline evaluation criteria for programs, design principles, and documentation of process and results (including program elimination or rejection decisions).

- Direct EKPC to perform integrated analysis of DSM potential on equal footing with supply-side resources in all future resource planning, including but not limited to Integrated Resource Plan ("IRP") and Certificate of Public Convenience and Necessity ("CPCN") proceedings. This should include allowing DSM resources to be a selectable resource together with supply-side resources in resource optimization modeling.

**Q. Are you sponsoring any exhibits to your testimony?**

A. Yes. I have prepared the following exhibits:

Exhibit MR-1: a copy of my résumé.

Exhibit MR-2: Industrial Heat Pumps: Electrifying Industry's Process Heat Supply (ACEEE).

Exhibit MR-3: Field Study of Ground Source Integrated Heat Pump – Final Report (Oak Ridge National Laboratory).

Exhibit MR-4: Manufactured Home Replacement Program – Pilot Evaluation (Energy Trust of Oregon / Opinion Dynamics Corporation)

Exhibit MR-5: A New State of the Art: Zero Energy Modular Multifamily Construction (VEIC)

Exhibit MR-6: Zero Energy Modular Factory Initiative (VEIC)

## IV. EKPC'S PROPOSED DSM PLAN WILL DELIVER ENERGY AND COST BENEFITS. IT SHOULD, HOWEVER, BE SIGNIFICANTLY EXPANDED.

### A. Summary of EKPC's Proposed Plan & Overarching Concerns

**Q. Please provide an overview of EKPC's requests in this proceeding.**

A. EKPC is requesting approval of three separate CPCNs, a site compatibility certificate for new generation, and DSM tariff changes, and other relief.[2]

EKPC seeks CPCNs: (a) to construct a 745 MW (nameplate) Integrated Combined Cycle Gas Turbine ("CCGT") at the Cooper Station; (b) to convert the Cooper Station Unit 2 (nameplate capacity 225 MW) to be capable of gas co-firing; and (c) to convert each of Spurlock Units 1-4 (combined nameplate capacity of 1,346 MW) to be capable of gas co-firing. EKPC emphasizes that the proposed Cooper CCGT is "the only addition to EKPC's

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[2] Application at 1, 19 (Nov. 20, 2024) ("Application").

existing generating capacity that is being proposed as part of this Application";[3] and that the Cooper CCGT proposal is also part of a "plan in total" that includes additional generation additions already approved, proposed, or to be proposed, in three other proceedings.[4] Additionally, EKPC seeks an "acknowledgment" that the proposed CCGT "will be the eventual replacement capacity for Cooper Station Unit 1 (nameplate capacity 100 MW)[5] under KRS 278.264,"[6] but has not proposed or requested retirement of any existing generating units. EKPC also proposes to expand and continue its DSM offerings established in Case No. 2019-00059.

**Q. Please summarize the DSM-EE program plan proposals.**

A. The proposed EKPC DSM portfolio includes four new DSM program tariffs, changes to the tariffs of three existing DSM programs, as well as the continuation of three existing programs without changes. Two of the programs target savings from C&I customers, while the rest are tailored for residential consumers. The following table lists the programs included in the DSM-EE proposal, provides short descriptions, and identifies proposed changes to existing programs:

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[3] Application at 5, ¶ 8.

[4] Application at ¶ 11 ("The three CPCN projects presented in this Application are needed, and represent a critical component of a single comprehensive plan, along with the resources presented in Case No. 2024-00129 and Case No. 2024-00310."); Application Ex. 2, Direct Testimony of Don Mosier on Behalf of East Kentucky Power Cooperative, Inc., Case No. 2024-00370, at 7 (Nov. 20, 2024) ("Mosier Direct") ("EKPC also anticipates seeking a CPCN for additional renewable energy as soon as next year"); Responses to Staff's First Information Request to East Kentucky Power Cooperative, Inc. dated December 20, 2024, Case No. 2024-00370, Question 1 at 2 (Jan. 3, 2025) ("EKPC Resp. to Staff Q1-1") ("All of the pending CPCN applications, and the New ERA CPCN application to be filed in early 2025, are part of a well-designed, comprehensive resource plan to provide the reasonable, least-cost solution for EKPC's Owner-Members. The Commission should look at the plan in total, because that is how it was assembled.").

[5] Mosier Direct at 16.

[6] Application at 19; Mosier Direct at 17-18.

*Table 1: Programs Included in EKPC's Proposed DSM Plan*

| **Program Name** | **Summary Description** | **Proposed Changes** |
|---|---|---|
| **New Programs** | | |
| High Efficiency Heat Pump (Residential) | Provides incentives to homeowners replacing a heat pump with a more efficient heat pump. | n/a |
| Commercial Advanced Lighting | Provides an incentive for small commercial businesses to replace inefficient light bulbs or light fixtures with LED lighting. | n/a |
| Commercial and Industrial Thermostat | Provides an incentive to qualifying businesses to replace traditional thermostats with self-learning thermostats. | n/a |
| Back-up Generator Control (Residential) | Provides annual incentive to retail participant in exchange for EKPC managing permanently installed whole-home back-up generators during peak energy events. | n/a |
| **Existing Programs - with proposed changes** | | |
| Button-Up Weatherization (Residential) | Provides incentives to participants with existing homes focused on building envelope measures including insulation and air sealing. | Add incentives for new measures.<br>Increase incentives due to increased measure costs. |
| CARES (Residential) | Income-qualified weatherization assistance program administered by Community Action Agencies and Affordable Housing Organizations; focus on insulation, air sealing, and heat pump measures. | Increase incentives due to increased measure costs. |
| Heat Pump Retrofit (Residential) | Provides incentives to participants with existing homes using electric resistance heat to convert to using a heat pump. | Increase incentives due to increased measure costs. |
| **Existing Programs - without changes** | | |
| Touchstone Energy® Home Program (Residential) | Provides incentives to home builders to increase home energy efficiency by 25% above minimum standards. | None |
| Direct Load Control (Residential) | Provides annual incentive to participants in exchange for EKPC managing water heater, center air conditioners or heat pumps, or thermostats during peak load events. | None |
| Electric Vehicle Home Charging Pilot (Residential) | Provides incentive to participants to encourage off-peak EV charging. | None |

**Q. How much does EKPC propose to spend in DSM to implement the proposed plans?**

A. The forecasted expenditures for all DSM-EE programs for the first 12 months of operation are estimated to be $7.8M excluding staff salaries.[7] This is roughly twice the level of investment EKPC made in DSM-EE in program year 2023.[8]

**Q. What energy and demand savings does EKPC expect to achieve as a result of the proposed DSM-EE plan changes?**

A. EKPC Witness Scott Drake reports the projected cumulative impacts of the proposed DSM-EE Plan from 2025 through 2039 at page 19 of his direct testimony.[9] Incremental annual energy savings vary slightly year-to-year, but are approximate 13,000 MWh in the 2026-2030 period.[10] In 2030, the projected level of annual savings reflects roughly 0.4% of EKPC's retail sales.[11] On a cumulative basis, EKPC proposes to pursue 69,792 MWh of energy savings over the 2026-2030 period, as well as 38 MW of winter peak demand reduction and 45 MW of summer peak demand reduction.[12]

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[7] Application Ex. 10, Direct Testimony of Scott Drake on Behalf of East Kentucky Power Cooperative, Inc., Case No. 2024-00370, at 21 (Nov. 20, 2024) ("Drake Direct").

[8] Application at 12, ¶ 27.

[9] If approved, the first year of the expanded DSM-EE Plan would be 2026.

[10] Drake Direct at 19 (providing cumulative savings projection, from which incremental annual savings can be approximated).

[11] Based on dividing actual 2023 sales by each of the high- and low-annual savings values in the preceding sentence. *See* Application Ex. 3, Direct Testimony of Julia J. Tucker on Behalf of East Kentucky Power Cooperative, Inc., Case No. 2024-00370 (Nov. 20, 2024) ("Tucker Direct"), Attach. JJT-3 (Actual 2023 sales reported as 13,465,331 MWh).

[12] Drake Direct at 19. EKPC's Response to Joint Intervenors' Supplemental Request 72(a)-(c) states that the peak MW reduction values reflect a combined total across currently existing and newly proposed or modified EE and DR programs. Responses to Joint Intervenors' Supplemental Requests for Information to East Kentucky Power Cooperative, Inc. dated January 17, 2025, Case No. 2024-00370, Question 72 (Jan. 31, 2025) ("EKPC Resp. to JI Q2-72").

**Q. What process did EKPC use to develop the proposed DSM-EE Plan?**

A. According to Company witness Drake, EKPC, and its owner-members, take multiple steps to determine which cost-effective measures and DSM-EE programs to develop and implement. The first step is to perform a DSM Technical Potential Study every three years. The second step is to engage with stakeholders. Specifically, the EKPC Collaborative reviews the cost effectiveness results from the Potential Study and recommends measures and programs for EKPC to consider. The third step engages owner-member cooperatives and EKPC staff experts, who based on their experience with the implementation of past measures, make final recommendations for which measures to include in the Plan. At the fourth step, an EKPC expert reviews the measure recommendations, their cost-effectiveness, as well as existing measures, to inform the updated program design. The fifth step of this process includes approvals from executive EKPC staff and the owner-members, and finally a request for approval of the Plan before the Commission.

**Q. What was the scope, including intended outputs, of the 2024 Potential Study?**

A. According to the 2024 Potential Study:[13]

> The study examines the potential to reduce electric consumption and peak demand through the implementation of DSM technologies and practices in residential, commercial, and industrial facilities. The 2024 Potential Study assessed energy efficiency potential and demand response throughout EKPC Members' service territories over fifteen years, from 2024 through 2038. The scope of this study distinguishes three types of energy efficiency potential: (1) technical, (2) economic, and (3) achievable.

Routinely, GDS potential studies distinguish these three types of potential.

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[13] Drake Direct, Attach. SD-7, GDS Assocs. Inc., EKPC 2024 Potential Study (Sept. 2024).

The Technical Potential is the theoretical maximum amount of energy use that could be displaced by DSM measures, disregarding all non-engineering constraints such as cost-effectiveness and the willingness of end users to adopt the measures.

The Economic Potential identifies "the subset of the technical potential that is economically cost-effective (based on screening with the Total Resource Cost ["TRC"] test) as compared to conventional supply-side energy resources."[14]

Finally, the Achievable Potential identifies a subset of economic potential considering real-world barriers and reflecting the amount of energy that efficiency can realistically be expected to displace. As in this Potential Study, achievable potential can be further subcategorized to maximum achievable potential ("MAP") and realistically achievable potential ("RAP"), with RAP being a subset of MAP based on the provision of assumed incentives that reflect a percentage of the measure's incremental measure costs.

**Q. Do you have any concerns about EKPC's process and proposed plan?**

A. I have a number of concerns regarding factors and EKPC choices that have led to a proposed plan that leaves cost-effective and achievable energy savings and demand flexibility untapped. This consequently leads to a higher capacity need for supply-side resources, a more expensive resource portfolio, and finally exposes ratepayers to unnecessary risks, as discussed by Witness Elizabeth Stanton. My overarching concerns are:

- EKPC's Proposed Plan includes energy and demand savings that fall well below the cost-effective, achievable potential estimated in the Potential Study.

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[14] *Id.* at 14.

- For a number of reasons, the potential levels as projected in the 2024 Potential Study underestimate EKPC's true demand-side resource potential.

I explore each of these concerns throughout my testimony providing examples and details as to how EKPC's assumptions have led to a proposed DSM plan that fails to capture even a small portion of the available energy and cost savings.

### B. EKPC's proposed DSM plan does not meet all Commission factors.

**Q. What standards does the proposed DSM plan need to meet?**

A. In approving any DSM plans the Commission must determine the reasonableness of the plan considering a non-exhaustive number of factors outlined in KRS 278.285(1).

**Q. Based on your review, does EKPC's proposed DSM plan meet these standards?**

A. No. There are three factors that particularly call for further investigation as the Commission reviews the EKPC proposed plan.

a) Whether a utility's proposed demand-side management programs are consistent with its most recent long-range integrated resource plan.[15]

As I further discuss in Section V.C, DSM resources have not been examined on a level playing field with supply-side resources. EKPC states that its goal was to "develop cost-effective resources on both the supply-side and demand-side."[16] But EKPC has not done the integrated analysis needed to meet that goal—not as part of developing the DSM Plan or as part of the 2022 IRP process. Without integrated portfolio modeling of alternatives, the least-cost and least-risk portfolio options were not identified or evaluated, and demand-side

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[15] KRS § 278.285(1)(d).

[16] Drake Direct at 13.

resources with lower costs than the proposed supply-side additions were not included in the DSM plan.

b) The extent to which the plan provides programs which are available, affordable, and useful to all customers.[17]

Although the programs in the EKPC plan are expected to deliver energy and cost savings, they are not available, affordable, and useful to all customers. For example, the incentives provided are unnecessarily limited to historical levels, and where increased, are only increased to reflect the higher costs of the measures. They could be ramped up to further reduce the high upfront cost associated with investing in EE, becoming affordable for more customers, while remaining cost-effective. Importantly, the proposed plan is also limited in the number of programs offered and the proposed spending, i.e., several cost-effective programs are not available at all, and a relatively small proportion of eligible customers will have the opportunity to participate before exhausting budgets for the available programs. In a further example, the proposed DSM-EE plan does not include behavioral demand response program offerings such as critical peak pricing, which has the largest RAP out of all the DR programs included in the 2024 Potential Study and is also among the lowest barrier, and therefore most accessible, programs that could be made available to all customers.

c) The specific changes in customers' consumption patterns which a utility is attempting to influence.[18]

While the DSM Plan as proposed does address specific end uses and consumption patterns, it unreasonably ignores or underinvests in cost-effective potential to reduce energy demand

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[17] KRS § 278.285(1)(g).
[18] KRS 278.285(1)(a).

during the peak periods that caused EKPC to claim a need for supply-side resource investments.

**Q. What is your recommendation with respect to the approval of the DSM plan?**

A. The proposed programs in EKPC's plan will result in energy and cost savings and are good steps towards an overall lower cost resource portfolio. However, EKPC's DSM-EE plan should be expanded. As currently developed, the plan leaves several savings opportunities untapped. If pursued these could further reduce costs, emissions, and risks for EKPC, its owner-members, and their customers. My overarching recommendation is that the Commission approve the planned programs but require EKPC to expand the portfolio of measures aiming to reach the RAP as projected in the 2024 Potential Study. I make a number of recommendations throughout my testimony as to how this expansion could be achieved.

### C. EKPC's proposed DSM plan is significantly smaller than other utilities.

**Q. How does EKPC's level of investment in DSM compare to other utilities?**

A. EKPC's level of investment is approximately 0.7% of its operating revenue, and the projected annual savings represent a 0.09% of its retail sales.[19] The American Council for an Energy-Efficient Economy ("ACEEE") develops a report and scorecard ranking the largest U.S. electric utilities on their policy and program efforts related to EE.[20] I recognize that the report uses data that are a few years old at the time of this testimony. However, it is still

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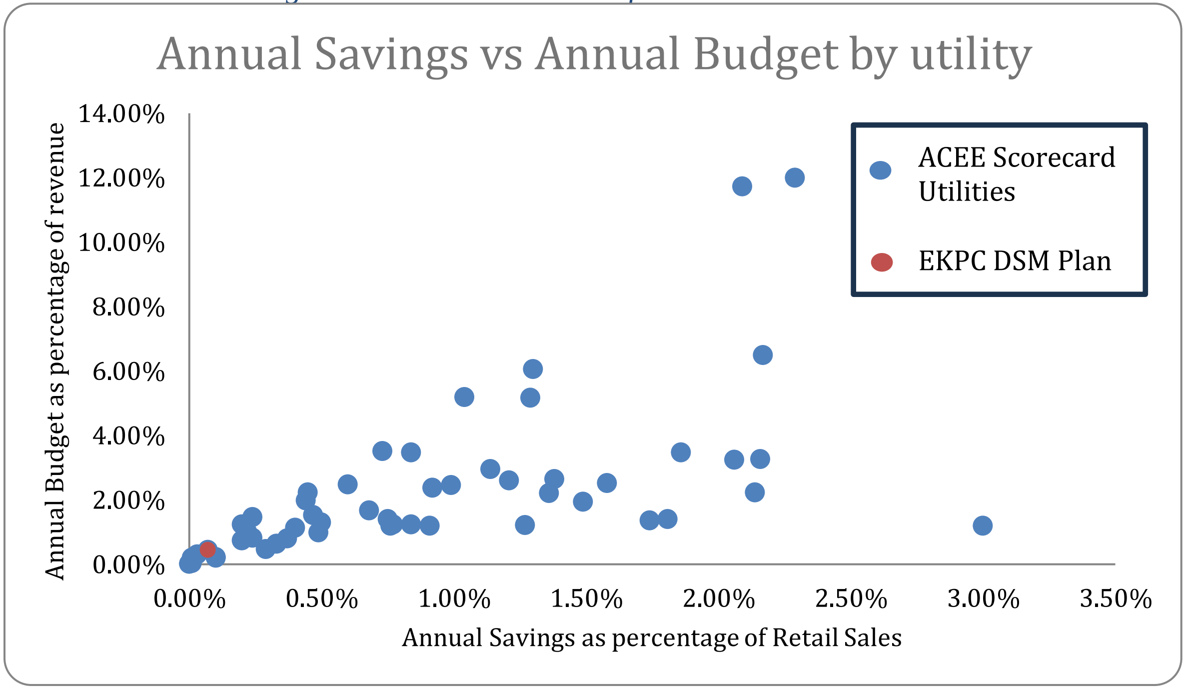
[19] These estimates reflect the proposed plan budget and savings, but are compared against 2023 operating revenue and sales (as reported in Mosier Direct at 3-4). EKPC projects significant increase in its retails sales (2025-2039 Load Forecast, provided in Tucker Direct, Attach. JJT-2, at 4). Thus, its operating revenue will also increase, resulting in the DSM budget and savings representing even lower percentages of the revenue and sales.

[20] Mike Specian et al., *2023 Utility Energy Efficiency Scorecard*, ACEEE (Aug.24, 2023), https://www.aceee.org/research-report/u2304.

illustrative to see that EKPC's proposed plan would rank among the utilities with the lowest EE investment and savings.

*Figure 1: EKPC's Plan Compared to Other Utilities*



## V. THE DSM PLAN FAILS TO PURSUE SIGNIFICANT COST-EFFECTIVE AND ACHIEVABLE DSM POTENTIAL IDENTIFIED IN THE POTENTIAL STUDY.

**Q. You mentioned an overarching concern that EKPC's proposed plan includes a level of savings that is well below the cost-effective, achievable potential estimated in the potential study. Please elaborate.**

A. As I mentioned earlier, the 2024 Potential Study was meant to be the foundation of the DSM planning process. The study identified possible residential, commercial, and industrial measures and evaluated those measures for cost effectiveness using the TRC test. According to EKPC, the results of the study were reviewed by the EKPC Collaborative, and then by owner-members and EKPC expert staff to design the proposed plan.[21]

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[21] Drake Direct at 7.

Despite this review, EKPC's plan does not appear to be meaningfully informed by the 2024 Potential Study. The notes of the EKPC Collaborative meetings, provided as attachments SD-1, SD-2, and SD-3 refer to the TRC scores, but do not include any discussion about the level of available savings and how programs should be designed to capture the RAP. Instead there seems to be an objective of minimizing free riders. In this case, the Potential Study amounts to little more than a theoretical exercise, missing the impact that it could otherwise have. By the end of this review, the proposed plan resulted in energy efficiency investment and savings falling well below the potential levels identified in the study. Specifically, by 2030, EKPC's proposed plan targets savings just over 10% of what the EKPC consultants identified as realistically achievable.

In this section, I first present the significant gap between the EKPC proposed savings as a portfolio of EE and DR measures with the MAP and RAP levels as identified in the potential study. Then, I dive deeper into the composition of the plan, as well as that of MAP and RAP, identifying end uses and EE measures that EKPC could target to increase the projected savings. I perform the same analysis for DR measures. I argue that this reduction from the identified RAP and MAP to the proposed DSM level is not reasonable, has not been justified by EKPC, and consequently leads to unnecessary costs for consumers, as EKPC pursues more expensive supply side resources.

### A. EKPC's plan ignores significant DSM potential.

**Q. Does EKPC's proposed plan capture a reasonable amount of the RAP presented in the 2024 DSM Potential Study?**

A. No. The 2024 DSM Potential Study found a total RAP savings potential of 416,739 MWh by 2028 and 625,682 MWh by 2030,[22] compared to just 69,972 MWh by 2030 from EKPC's plan. Because the Potential Study estimates savings starting in 2024, for all numbers reported in this testimony I am delaying these savings to approximate a 2026 starting year (i.e., comparing EKPC's planned savings by 2030 to reflect a five-year period 2026-2030, against RAP and MAP values by 2028 to reflect a five-year period 2024-2028).[23] The EKPC plan leaves approximately 350,000 MWh of RAP savings untapped by the last year of the five-year period. These energy savings are reasonably achievable and cost-effective. The comparison with the MAP values leaves a gap of approximately 530,000 MWh. Importantly, this gap also amounts to 135–441 MW of potential winter capacity reductions from DSM that were left on the table by EKPC in deciding not to pursue these savings (these numbers do not include the potential savings from interruptible rates, as EKPC stated that these MW are already accounted for in the load forecast).[24] Winter capacity need is the biggest driver behind EKPC's petition, and therefore such a large gap between the achievable potential identified in the potential study and the amounts reflected in the DSM-EE Plan is not

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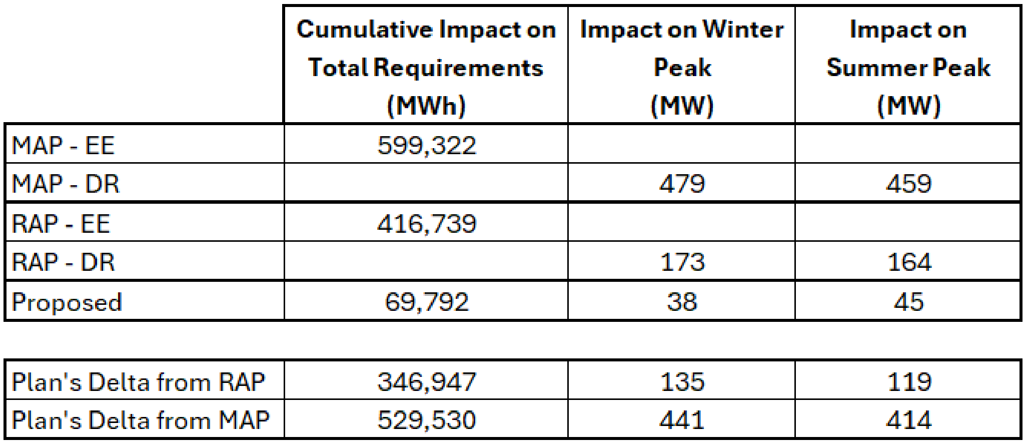
[22] Attach. SD-7, App. C.

[23] There are two considerations with comparing EKPC plan savings against the projected RAP and MAP values with a two year delay: (a) the potential might have slightly changed if some of those savings opportunities have been addressed (and are thus not available in 2026), (b) some savings from existing programs are actually pursued in 2025 and included in the Company's reported plan savings (thus the aggregate potential against which I compare them would need to have some programs starting in 2025, and some in 2026). None of these factors would result in a material change in the comparison. Thus, for simplicity and transparency, I do not further adjust the potential values.

[24] EKPC Resp. to JI Q2-65(c)

reasonable. Table 2 summarizes the RAP and MAP levels from the Potential Study, as well as the savings levels proposed in EKPC's DSM-EE Plan by 2030. Figures 2, 3, and 4 juxtapose the expected savings of EKPC's proposed plan with the RAP and MAP levels as calculated in the Company's 2024 Potential Study (MAP and RAP values delayed by two years compared to the Potential Study, excluding savings from interruptible rates).

*Table 2: EKPC's Plan Savings Compared to RAP and MAP Levels for the Five-Year Period Starting in 2026*



| | Cumulative Impact on Total Requirements (MWh) | Impact on Winter Peak (MW) | Impact on Summer Peak (MW) |
|---|---|---|---|
| MAP - EE | 599,322 | | |
| MAP - DR | | 479 | 459 |
| RAP - EE | 416,739 | | |
| RAP - DR | | 173 | 164 |
| Proposed | 69,792 | 38 | 45 |

| | | | |
|---|---|---|---|
| Plan's Delta from RAP | 346,947 | 135 | 119 |
| Plan's Delta from MAP | 529,530 | 441 | 414 |

*Figure 2: Impact on Total Energy Requirements from MAP, RAP, and EKPC Proposed DSM Plan (MWh)*

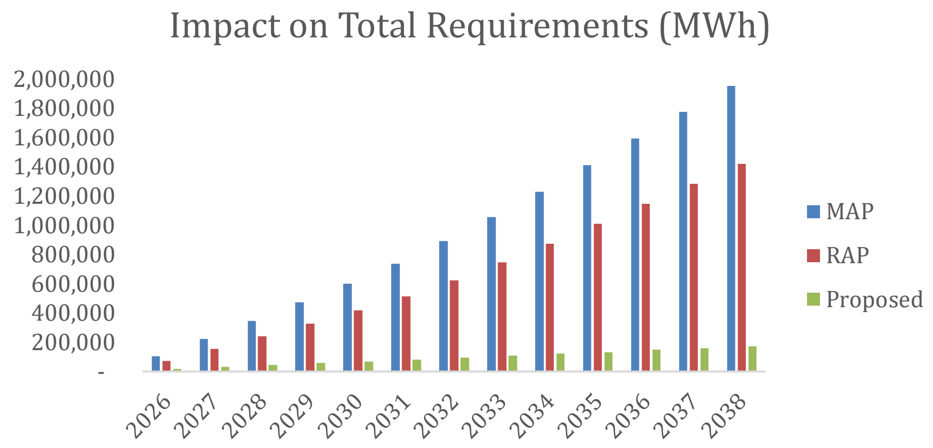


*Figure 3: Impact on Winter Peaк from MAP, RAP, and EKPC Proposed DSM Plan (MW)*

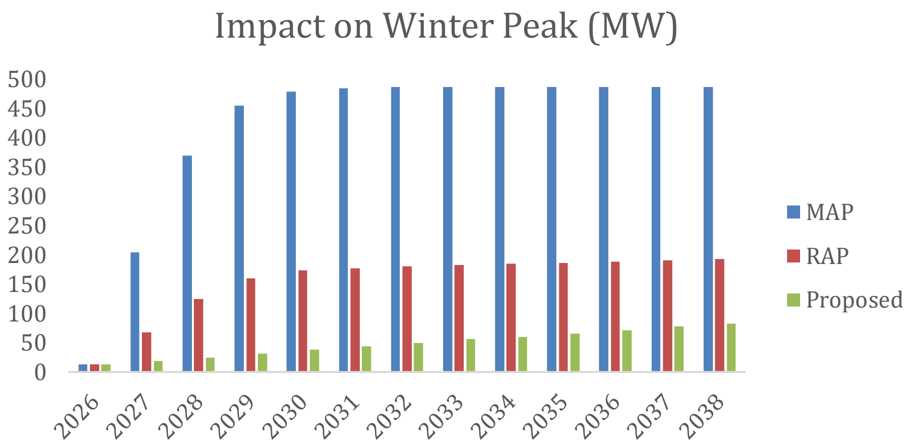
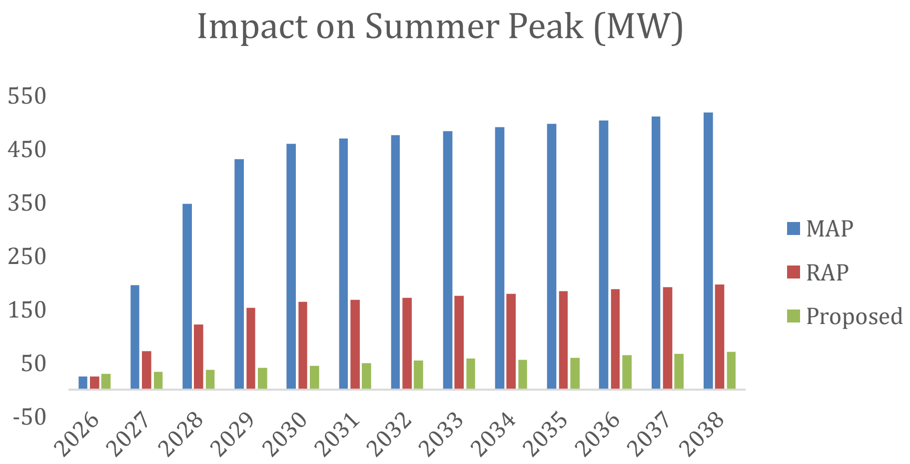


*Figure 4: Impact on Summer Peak from MAP, RAP, and EKPC Proposed DSM Plan (MW)*



**Q. What is your recommendation with respect to the savings that EKPC should pursue in its DSM plan?**

Q. At minimum, EKPC should develop a DSM-EE plan pursuing the RAP level of savings, i.e., target cumulative savings of 400,000 MWh by 2030, and winter peak savings of 173 MW. As I explain in Section VII, the RAP level identified in the Potential Study understates the realistically achievable (and cost-effective) savings and should, thus, serve as a minimum for EKPC's plan.

### B. EKPC has not provided a reasonable explanation for pursuing only a small fraction of the identified RAP by 2030.

**Q. Has EKPC provided an explanation for pursuing a plan with savings well below the identified RAP?**

A. No. When asked to explain why EKPC is not proposing a DSM plan to achieve all, or even a majority of, the RAP, the provided response was that EKPC and its owner-member expert staff identified the programs in the proposed plan as "top priority DSM programs for the rural Kentuckians served."[25] In a supplemental response EKPC further stated that a group of qualified experts with significant experience in Kentucky met on March 25, 2024 and that:[26]

> Based on cost effective DSM programs identified by the 2024 Potential Study, the group of experts pinpointed needed changes to existing DSM programs and which new DSM programs are most needed by and most useful for the rural end-use members. EKPC is requesting Commission approval for the DSM programs recommended by the experts. No documentation of the decision making was generated.

Still EKPC never provided an explanation for why additional achievable and cost-effective programs, beyond the "*most* needed" and "*most* useful," were not included in the plan. In

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[25] EKPC Resp. to JI Q1-61.
[26] EKPC Resp. to JI Q2-41(a).

making the choice to only pursue the "*most*" useful, EKPC fails to make several other useful programs available to customers, which, based on their positive cost-effectiveness scores, would lead to an overall lower cost portfolio compared to additional investment in supply-side alternatives.

**Q. Did the Potential Study examine different DSM portfolios based on different spending scenarios?**

A. Yes. Specifically:[27]

> The GDS Team calculated estimated savings for each EKPC program at three different spending scenarios: $7.4 million (Base), $5.4 million (Low), and $11.4 million (High). Each scenario is an increase over what EKPC spent in 2023. The first establishes program-level budgets and a total overall budget of $7.4 million, which represents a nearly $4 million increase over the 2023 spending of $3.4 million. The second scenario represents a 50% increase over the 2023 spending levels, and the third scenario represents a 200% increase over the 2023 spending levels.

**Q. Have EKPC or GDS provided information on how these scenarios were developed or used to inform the proposed plan?**

A. To a very limited degree. According to EKPC's response to Request JI 1-60:

> The Base spending scenario came from the work of EKPC program managers. They determined the program budgets that would result from estimates of higher incentives and greater participation in current and proposed programs. The High spending level is 200% higher than EKPC's 2023 DSM budget. The Low spending level is 50% higher than the 2023 DSM budget.

The Potential Study or EKPC's application does not contain information about how the scenario results were evaluated to inform the proposed plan. Again, it appears that the plan was primarily the result of EKPC's selection of certain programs and the use of historical incentives, rather than an intentional design to maximize energy and cost savings for owner-

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[27] Attach. SD-7 at 39.

members and their customers. Instead, EKPC should have set savings targets—without arbitrary limits on incentives or budgets—aiming to maximize the amount of cost-effective EE and DR achieved.

For example, when I compare the DR savings in the Base and High Scenarios, I find that the Base scenario results in 12.1 MW of winter peak reduction in 2030, while the High scenario results in 35.9 MW of winter peak reduction, i.e., three times that of the Base scenario with a budget that is only 50% higher.[28] In fact, the cost of winter demand saved in the High scenario is only $75.65/kW (and $30.83/kW for summer savings), far less than the avoided cost used to determine cost effectiveness.[29] It is unreasonable that EKPC is not pursuing at least this level of savings.

### C. EKPC's supply- and demand-side resource planning processes are inconsistent and siloed.

**Q. Did EKPC evaluate demand- and supply-side resources on a level playing field?**

A. No. Despite including both supply- and demand-side plans in this application, EKPC evaluated each of them separately, missing the opportunity to develop a lower cost resource portfolio for its owner-members and their customers. The DSM plan was mainly developed based on EKPC and owner-member expert program selections. DSM resources were then incorporated in the load forecast, which is used in EKPC's supply side resource planning. Thus, DSM resources were not offered as a selectable resource in capacity expansion modeling, denying them the ability to compete on a level playing field with other resources.[30]

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[28] Based on Appendix D of Attach. SD-7.

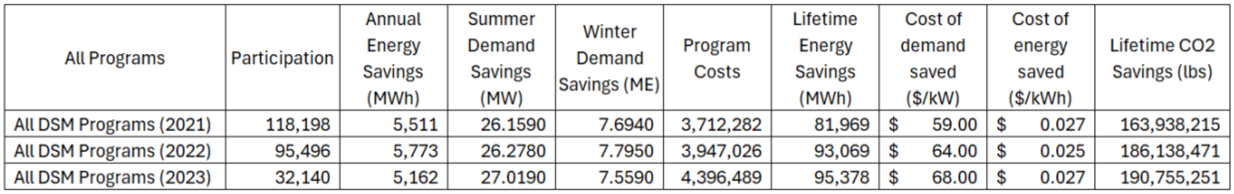
[29] Attachment SD-8 notes that the avoided generation capacity cost is assumed to be $174.60 per kW-year (no escalation). Drake Direct, Attach. SD-8, DSM Program Assumption Sheets.

[30] EKPC Resp. to JI Q2.68.

**Q. How do the cost of energy and demand saved compare to that of the proposed supply side resources?**

A. As EKPC's goal is to develop cost-effective resources on both the supply-side and demand-side,[31] it is useful to compare the cost of energy and demand saved from DSM resources to that of the proposed supply-side resources. Reviewing EKPC's 2021, 2022, and 2023 DSM reports, provided as Attachments SD-4, SD-5, and SD-6, the cost of demand and energy saved is $59–64/kW saved, and 0.025–0.027/kWh saved. The costs of the proposed programs are comparable as explained in Section VI(A) and VI(B).

*Table 3: System Summary of 2021, 2022, and 2023 DSM Program Savings*



| All Programs | Participation | Annual Energy Savings (MWh) | Summer Demand Savings (MW) | Winter Demand Savings (ME) | Program Costs | Lifetime Energy Savings (MWh) | Cost of demand saved ($/kW) | Cost of energy saved ($/kWh) | Lifetime CO2 Savings (lbs) |
|---|---|---|---|---|---|---|---|---|---|
| All DSM Programs (2021) | 118,198 | 5,511 | 26.1590 | 7.6940 | 3,712,282 | 81,969 | $ 59.00 | $ 0.027 | 163,938,215 |
| All DSM Programs (2022) | 95,496 | 5,773 | 26.2780 | 7.7950 | 3,947,026 | 93,069 | $ 64.00 | $ 0.025 | 186,138,471 |
| All DSM Programs (2023) | 32,140 | 5,162 | 27.0190 | 7.5590 | 4,396,489 | 95,378 | $ 68.00 | $ 0.027 | 190,755,251 |

To put these numbers in perspective the avoided costs (in 2025) used for the TRC calculations in the Potential Study were:

- Avoided electricity energy costs: $45.96/MWh;
- Avoided generation capacity cost: $174.6/kW-yr;
- Avoided transmission capacity cost: $35.76/kW-yr;
- Avoided distribution capacity cost: $4.93/kW-yr.[32]

Thus, the demand-side resources are more economic than supply-side resources as approximated through avoided cost estimates.

If, on the other hand, we were to compare the CCGT with a portfolio of DSM measures that could provide equivalent firm capacity and energy (assuming that it would be feasible to

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[31] Drake Direct at 13.

[32] Attach. SD-8. Additional details for seasonal values and annual escalation are provided in EKPC's Response to JI Q1-57.

scale DSM at this level), the cost of that DSM portfolio would again be lower than that of the CCGT. I am not suggesting that such a replacement is feasible. I argue, however, that a proper evaluation of both supply-side and demand-side resources would have resulted in a portfolio with more DSM resources and a lower supply-side capacity need (this could mean a smaller size CCGT, or a delayed need for that resource). I provide the calculations below for illustrative purposes (although a proper evaluation would need a capacity expansion model):[33]

- The CCGT would provide 745 MW of nameplate capacity. Using PJM's Effective Load Carrying Capability ("ELCC") Class Ratings for the 2025/2026 Delivery Year, this would equate to 540 MW of firm capacity.
- Assuming the CCGT would operate with a 40% capacity factor, it would generate 2,610 GWh/year.
- Assuming a lifetime of 35 years and a discount rate of 5.2%, the annualized cost of the CCGT (capital cost of $1.32 billion) would be $82.5 million. Fixed and variable operations and maintenance costs would add another $30 million/yr, combined making for annual costs of over $112 million. This does not consider fuel costs, which would amount to more than $60 million per year if I assume a natural gas price of $3.94/Mcf.[34]
- A DSM portfolio with the same magnitude of demand and energy savings would cost roughly $110 million (assuming that EE resources provide the

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[33] The calculations are provided for illustrative purposes and use some generic values for CC resources from the 2024 Annual Technology Baseline ("ATB") from the National Renewable Energy Laboratory ("NREL") or other assumptions that are explicitly stated in the testimony.

[34] EKPC Resp. to Staff Q1-58(d).

required energy at $0.027/kWh, and DR resources the required demand at $68/kW-yr, and not including any synergies—realistically, however, EE measures could also further reduce peak demand).

Again, DSM would be more economic.

EKPC's choice not to consider DSM portfolios with higher targeted savings leads to an increased need for supply-side resource additions and capital investments. Redirecting some or all those investment dollars towards building up cost-effective EE and DR programs and consequently reducing in size, delaying, or even offsetting the need for more costly supply-side resources would benefit EKPC, its owner-members, and their customers.

**Q. Are there additional benefits of pursuing DSM?**

A. Yes. As already captured through the avoided cost analysis, DSM resources offset energy costs as well as costs of incremental generation, transmission, and distribution capacity. However, DSM resources have additional grid benefits, as well as health and emissions benefits.[35]

In terms of additional grid benefits, DSM resources increase the reliability and resilience of the grid by making the system less vulnerable to outages. They avoid risks related to long lead-time investments, which is particularly important in this era of significant load growth uncertainty, i.e., they would not carry the risk of being left stranded for either economic or policy reasons, or because the projected load growth does not materialize. They can be

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[35] U.S. EPA, *Quantifying the Multiple Benefits of Energy Efficiency and Renewable Energy: A Guide for State and Local Governments* (2018), https://www.epa.gov/sites/default/files/2018-07/documents/epa_slb_multiple_benefits_508.pdf .

deployed quickly and are scalable. DSM resources also contribute to the fuel diversity of the grid, reducing the associated risks and the consumers' exposure to fuel price volatility.

## VI. EKPC'S PROGRAM DESIGN LEAVES UNTAPPED SAVINGS ACROSS ALL END-USES.

### A. EKPC's plan fails to pursue cost-effective and achievable EE programs.

**Q. Please summarize your findings and recommendations with respect to the EE measures that EKPC includes in its plan.**

A. At the portfolio level, I find that EKPC's plan falls short of the identified potential, and should significantly increase its DSM investment to at least reach the identified RAP. Reviewing the composition of the EKPC portfolio, I find that although it includes some programs targeting high potential end-uses, these are not sufficient (as currently planned). Residential weatherization and HVAC measures should be ramped up, while additional programs targeting behavioral changes and water heating should be included. For C&I customers, the DSM offerings should significantly expand, both ramping up the lighting and thermostat programs, as well as including whole building and custom programs, and measures tailored to achieve winter demand savings. Those could include measures around motors, refrigeration, and additional HVAC measures.

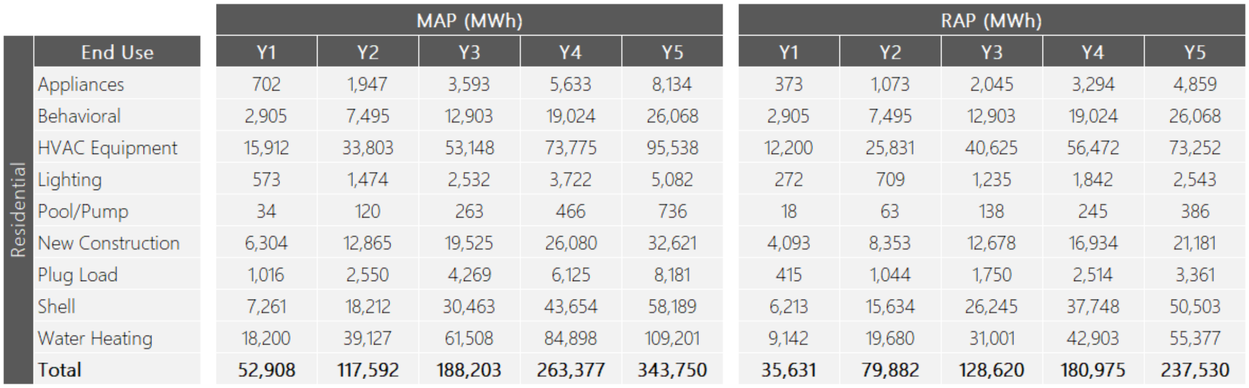
#### 1. <u>Residential Programs</u>

**Q. Are there any residential measures that have a high RAP but are not included in EKPC's DSM plan?**

A. Yes. Although the Potential Study does not report the RAP or MAP of specific measures, Appendix C provides the potential by End-Use.

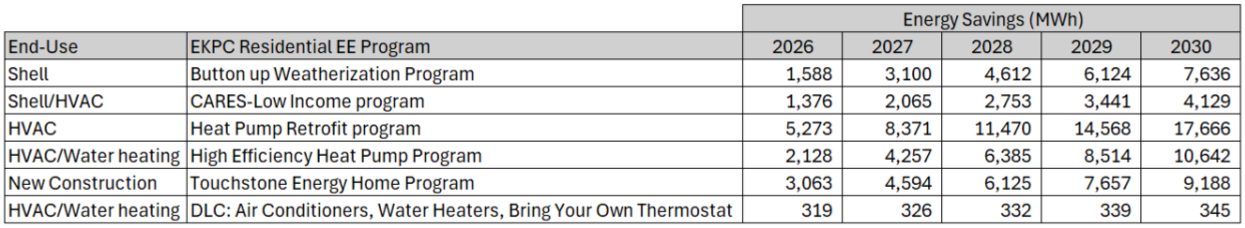
- Table 4 replicates the RAP and MAP energy savings by residential end-use for a five-year period. The end use categories with the highest potential levels for residential customers include HVAC Equipment, Shell, and Water Heating.
- Table 5 includes the energy savings for all residential EE measures included in EKPC's DSM plan. The table includes impacts from the DLC Program, although this is primarily a DR program. However, it also results in EE savings by managing water heating load.

*Table 4: Residential EE - Cumulative MAP & RAP Savings by End-Use (MWh)*[36]



| | | MAP (MWh) | | | | | RAP (MWh) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | End Use | Y1 | Y2 | Y3 | Y4 | Y5 | Y1 | Y2 | Y3 | Y4 | Y5 |
| Residential | Appliances | 702 | 1,947 | 3,593 | 5,633 | 8,134 | 373 | 1,073 | 2,045 | 3,294 | 4,859 |
| | Behavioral | 2,905 | 7,495 | 12,903 | 19,024 | 26,068 | 2,905 | 7,495 | 12,903 | 19,024 | 26,068 |
| | HVAC Equipment | 15,912 | 33,803 | 53,148 | 73,775 | 95,538 | 12,200 | 25,831 | 40,625 | 56,472 | 73,252 |
| | Lighting | 573 | 1,474 | 2,532 | 3,722 | 5,082 | 272 | 709 | 1,235 | 1,842 | 2,543 |
| | Pool/Pump | 34 | 120 | 263 | 466 | 736 | 18 | 63 | 138 | 245 | 386 |
| | New Construction | 6,304 | 12,865 | 19,525 | 26,080 | 32,621 | 4,093 | 8,353 | 12,678 | 16,934 | 21,181 |
| | Plug Load | 1,016 | 2,550 | 4,269 | 6,125 | 8,181 | 415 | 1,044 | 1,750 | 2,514 | 3,361 |
| | Shell | 7,261 | 18,212 | 30,463 | 43,654 | 58,189 | 6,213 | 15,634 | 26,245 | 37,748 | 50,503 |
| | Water Heating | 18,200 | 39,127 | 61,508 | 84,898 | 109,201 | 9,142 | 19,680 | 31,001 | 42,903 | 55,377 |
| | **Total** | **52,908** | **117,592** | **188,203** | **263,377** | **343,750** | **35,631** | **79,882** | **128,620** | **180,975** | **237,530** |

*Table 5: Residential EE - Cumulative Savings by End-Use in EKPC Proposed Plan (MWh)*[37]



| | | Energy Savings (MWh) | | | | |
|---|---|---|---|---|---|---|
| End-Use | EKPC Residential EE Program | 2026 | 2027 | 2028 | 2029 | 2030 |
| Shell | Button up Weatherization Program | 1,588 | 3,100 | 4,612 | 6,124 | 7,636 |
| Shell/HVAC | CARES-Low Income program | 1,376 | 2,065 | 2,753 | 3,441 | 4,129 |
| HVAC | Heat Pump Retrofit program | 5,273 | 8,371 | 11,470 | 14,568 | 17,666 |
| HVAC/Water heating | High Efficiency Heat Pump Program | 2,128 | 4,257 | 6,385 | 8,514 | 10,642 |
| New Construction | Touchstone Energy Home Program | 3,063 | 4,594 | 6,125 | 7,657 | 9,188 |
| HVAC/Water heating | DLC: Air Conditioners, Water Heaters, Bring Your Own Thermostat | 319 | 326 | 332 | 339 | 345 |

Reviewing those tables, it becomes apparent that EKPC is missing out on significant savings across all end-uses. In the RAP scenario, Shell and HVAC Equipment are the leading end-

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[36] Attach. SD-7, App. C.

[37] EKPC Resp. to JI Q2-55(g) at 3-7, 10.

uses, accounting for more than 50% of the potential.[38] Programs targeting savings for these two leading end-uses, although they are included in EKPC's plan, have projected savings that are significantly lacking compared to their MAP and RAP values. The combined cumulative savings from all residential programs in EKPC's plan is 49,606 MWh, which is only a fraction of just the cumulative 5-year RAP of 123,755 MWh identified for the two leading end-uses in the Potential Study (shell and HVAC). This indicates that EKPC should ramp up existing programs, as well as introduce new ones.

**Q. Does the EKPC proposed budget plan include all identified RAP potential for residential EE measures with relatively high winter season impacts?**

A. No. Although the above tables summarize potential and planned levels of energy savings by end-use and program, an important consideration for EKPC should also be the impact on winter peak needs. Winter heating efficiency measures can have a dramatic impact on winter peak demand need, in addition to saving energy. As already explained, the EKPC plan for EE significantly lacks in residential weatherization and HVAC targeted savings.

**Q. An end use that has high RAP value is water heating. Did EKPC design a program targeting this end use?**

A. Not to a satisfactory degree. The EKPC plan includes the DLC program which targets savings from water heating to a limited degree. The program is mainly designed to reduce peak demand to provide load relief to the grid through the installation of load control devices on electric water heaters.[39] It can also reduce energy usage. DLC is a continuing program, but EKPC is not planning to install new switches. All new enrollments will be Wi-Fi enabled

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[38] Attach. SD-7 at 20.
[39] Drake Direct at 31.

thermostats provided by the end-use member under the "Bring Your Own Thermostat" ("BYOT") option.[40] Only a portion of those savings, which I estimate to be approximately 185 MWh (out of the 345 MW by 2030), can be attributed to managing water heating load. EKPC also provides incentives for heat pump water heaters through the new High Efficiency Heat Pump ("HEHP") Program, with an annual incremental impact of approximately 521 MWh. The two programs together would result in cumulative savings by 2030 of 2,800 MWh, compared to the 82,929 MWh (RAP) and 161,665 MWh (MAP) of cumulative savings potential for the residential water heating end use.[41]

**Q. Programs targeting behavioral changes also have high RAP savings according to the Potential Study. Does EKPC include any program for this category?**

A. No. Behavioral measures might not provide savings as long-lasting as shell or HVAC equipment measures, but they can be considered a low hanging fruit due to the low upfront cost. Reviewing the DSM Annual Report 2021 and the DSM Annual Report 2022, provided as attachments SD-4 and SD-5 respectively, as well as Appendix A, I noticed that a behavioral program (energy audit) existed for those years. However, the program reported low participation numbers and consequently low savings, while costs per kWh were higher than other measures. The stark contrast between the DSM reports and the very high RAP reported for behavioral measures requires investigation from EKPC, as the past programs offered might not have been well designed. For example, Duke Energy Kentucky not only offers a residential energy assessment program, named Home Energy House Call ("HEHC"),

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[40] Attach. JJT-2 at 31.
[41] Attach. SD-7, App. C.

but has recently expanded it.[42] The program's goal is "to empower customers to better manage their energy usage and cost." It has a TRC of 1.38 and its load impacts from July 2023 through June 2024 amounted to 0.05% of residential electricity sales. The program was recently expanded and now offers single family renters, condo/townhomes/manufactured homeowners, and renters the ability to choose a virtual, phone or web-based audit for their home (in addition to the original walk though assessment option).

**Q. Have you conducted any analysis for the cost ($/kWh) of the continuing and new (proposed) residential EE programs?**

A. Yes. Table 6 lists the programs as well as their expected energy and demand savings, the incentives provided to participants, and the costs to participants and EKPC. The table also includes the TRC values for the measures which range from 2.21 to 7.97. The cost of energy savings is from $0.019/kWh to $0.049/kWh in 2026. It is worth noting that only the avoided cost of energy is assumed to be $0.0385–0.0567/kWh in 2026 (depending on the season and on/off peak hours),[43] with additional savings including avoided generation, transmission, and distribution capacity costs.[44] The calculated costs are consistent with what EKPC has reported in the DSM reports for past years. The U.S. Energy Information Administration ("EIA") estimates the levelized cost of new combined cycle generation like the one proposed

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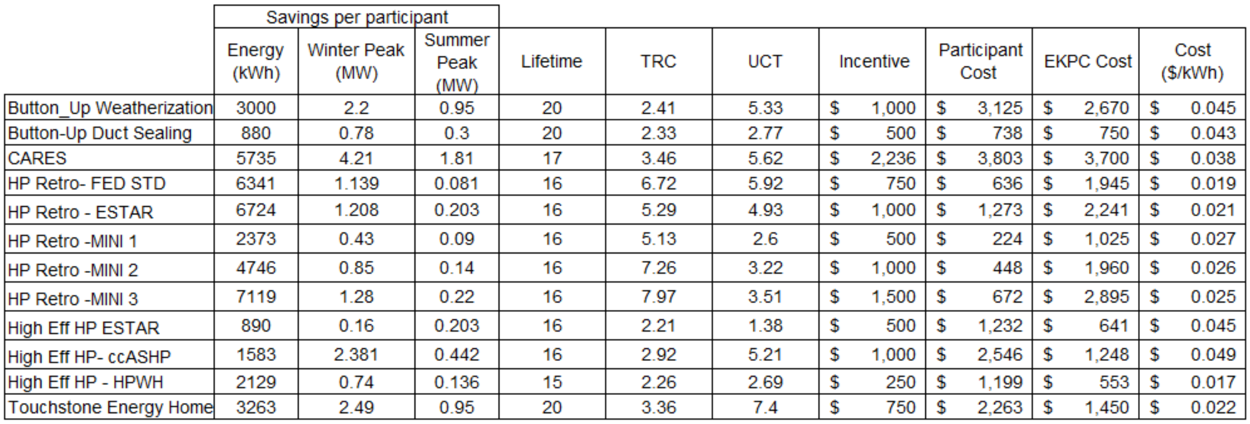
[42] Annual Status Report, Adjustment of the DSM Cost Recovery Mechanisms for both gas and electric service (DSM Riders), and Amended Tariff Sheets for Gas Rider DSMR and Electric Rider DSMR (Application), *In re the Annual Cost Recovery Filing for Demand Side Management by Duke Energy Kentucky, Inc*., Case No. 2024-00352, at ¶¶ 39-47 (Nov. 1, 2024).

[43] EKPC's Resp. to JI Q1-57(c).

[44] Attach.SD-8. EKPC's Program Assumption Sheets reflect avoided cost values of $174.60 per kW-year for avoided generation capacity costs, $35.76 per kW-year for avoided transmission capacity costs, $4.93 per kW-year for avoided distribution capacity costs.

in this CPCN to be $45.43/MWh.[45] The levelized cost of the EKPC proposed CCGT, following the same assumptions as outlined in Section V(C) above, would be above $60/MWh.

*Table 6: Impact and Cost Summary of Residential EE Programs*[46]



|  | Savings per participant |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Energy (kWh) | Winter Peak (MW) | Summer Peak (MW) | Lifetime | TRC | UCT | Incentive | Participant Cost | EKPC Cost | Cost ($/kWh) |
| Button_Up Weatherization | 3000 | 2.2 | 0.95 | 20 | 2.41 | 5.33 | $ 1,000 | $ 3,125 | $ 2,670 | $ 0.045 |
| Button-Up Duct Sealing | 880 | 0.78 | 0.3 | 20 | 2.33 | 2.77 | $ 500 | $ 738 | $ 750 | $ 0.043 |
| CARES | 5735 | 4.21 | 1.81 | 17 | 3.46 | 5.62 | $ 2,236 | $ 3,803 | $ 3,700 | $ 0.038 |
| HP Retro- FED STD | 6341 | 1.139 | 0.081 | 16 | 6.72 | 5.92 | $ 750 | $ 636 | $ 1,945 | $ 0.019 |
| HP Retro - ESTAR | 6724 | 1.208 | 0.203 | 16 | 5.29 | 4.93 | $ 1,000 | $ 1,273 | $ 2,241 | $ 0.021 |
| HP Retro -MINI 1 | 2373 | 0.43 | 0.09 | 16 | 5.13 | 2.6 | $ 500 | $ 224 | $ 1,025 | $ 0.027 |
| HP Retro -MINI 2 | 4746 | 0.85 | 0.14 | 16 | 7.26 | 3.22 | $ 1,000 | $ 448 | $ 1,960 | $ 0.026 |
| HP Retro -MINI 3 | 7119 | 1.28 | 0.22 | 16 | 7.97 | 3.51 | $ 1,500 | $ 672 | $ 2,895 | $ 0.025 |
| High Eff HP ESTAR | 890 | 0.16 | 0.203 | 16 | 2.21 | 1.38 | $ 500 | $ 1,232 | $ 641 | $ 0.045 |
| High Eff HP- ccASHP | 1583 | 2.381 | 0.442 | 16 | 2.92 | 5.21 | $ 1,000 | $ 2,546 | $ 1,248 | $ 0.049 |
| High Eff HP - HPWH | 2129 | 0.74 | 0.136 | 15 | 2.26 | 2.69 | $ 250 | $ 1,199 | $ 553 | $ 0.017 |
| Touchstone Energy Home | 3263 | 2.49 | 0.95 | 20 | 3.36 | 7.4 | $ 750 | $ 2,263 | $ 1,450 | $ 0.022 |

**Q. Given the low cost of those resources, how could EKPC increase participation to achieve higher savings?**

A. The lowest cost program is the Heat Pump Retrofit Program. As expected, the measures also have high TRC values, showing that the savings are multiple times their cost. However, the up-front cost for participants remains high and can hinder participation. If EKPC increased the incentive levels for this program (more than currently proposed), additional energy and cost savings could be achieved. Similarly, the High Efficiency Heat Pump – Water Heater has high UCT and TRC scores, but the incentive provided is low resulting in high upfront costs for participants. Increasing the incentive for this program would result in energy and

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[45] US Energy Info. Admin., *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2023*, at 8 (Apr. 2023), https://www.eia.gov/outlooks/aeo/electricity_generation/pdf/AEO2023_LCOE_report.pdf. The levelized cost for Combined Cycle generation is estimated to be $42.72/MWh, which inflated to $2024 is $45.43/MWh.

[46] The table is based on information from Attach. SD-8, as well as the Attachment to EKPC Resp. to JI Q2-58, entitled “JI2.58-EKPC_DSM_Budgets”. The cost is calculated based on the 2026 program spending (Attach. JI 2-58), and the estimated lifetime energy and demand savings for 2026 participants (Attach. SD-8).

cost savings. In addition to the water heater, EKPC should consider higher incentives for the Touchstone Energy Program, the Federal Standard and Energy Star Heat Pumps of the Heat Pump Retrofit program, and the cold climate air source heat pump of the High Efficiency Heat Pump program, all of which are estimated to have a high impact on winter peak. EKPC could also support the increase in innovative financial tariffed on-bill repayment programs to lower first cost barriers to participation, as discussed elsewhere in my testimony.

**Q. What are your recommendations for the residential EE programs that should be included in the EKPC plan?**

A. EKPC should ramp up its residential program offerings, especially the ones targeting inefficient electric heating, through both increased incentives and increased spending to ensure the availability of the program for all eligible and interested customers. Furthermore, EKPC should establish new programs targeting savings from water heating, as well as behavioral programs.

### 2. <u>C&I Measures</u>

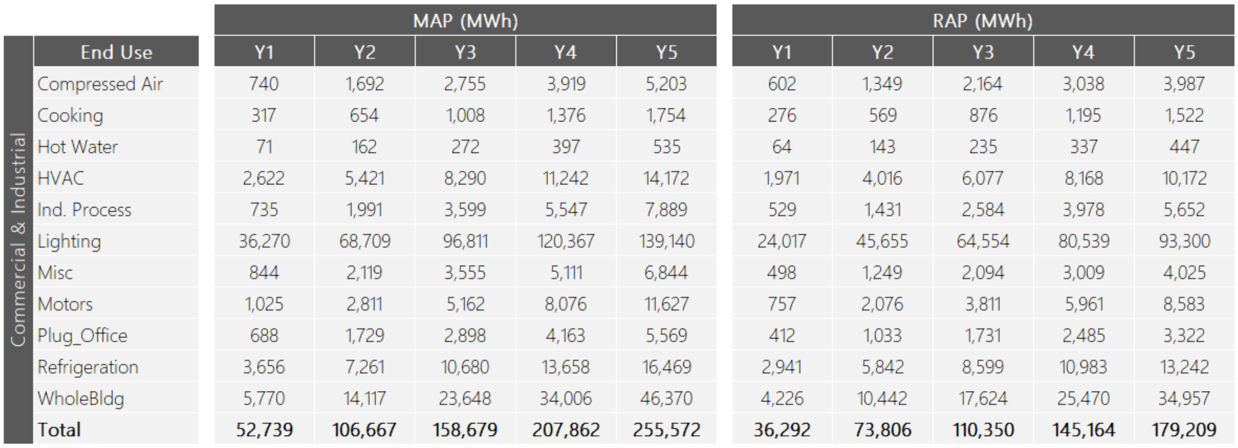
**Q. Are there any Commercial & Industrial ("C&I") EE measures that have a high RAP but are not included in EKPC's DSM plan?**

A. Yes.

- Table 7 includes the MAP and RAP energy savings by End-Use for C&I customers. The end-use categories with the highest potential levels for C&I customers include lighting and whole building programs, while HVAC, motors, and refrigeration also have high potential values.

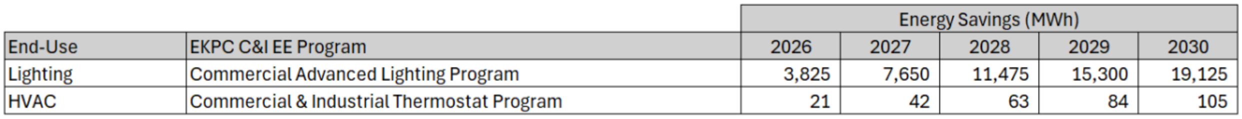
- Table 8 includes the energy savings by program for all C&I EE measures included in EKPC's DSM plan. The only C&I EE measures included in EKPC's existing tariffs and proposed plan are commercial lighting and commercial thermostats, which is a very limited C&I portfolio.

*Table 7: C&I EE - Cumulative MAP & RAP Savings by End-Use (MWh)*[47]



| | | MAP (MWh) | | | | | RAP (MWh) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | End Use | Y1 | Y2 | Y3 | Y4 | Y5 | Y1 | Y2 | Y3 | Y4 | Y5 |
| Commercial & Industrial | Compressed Air | 740 | 1,692 | 2,755 | 3,919 | 5,203 | 602 | 1,349 | 2,164 | 3,038 | 3,987 |
| | Cooking | 317 | 654 | 1,008 | 1,376 | 1,754 | 276 | 569 | 876 | 1,195 | 1,522 |
| | Hot Water | 71 | 162 | 272 | 397 | 535 | 64 | 143 | 235 | 337 | 447 |
| | HVAC | 2,622 | 5,421 | 8,290 | 11,242 | 14,172 | 1,971 | 4,016 | 6,077 | 8,168 | 10,172 |
| | Ind. Process | 735 | 1,991 | 3,599 | 5,547 | 7,889 | 529 | 1,431 | 2,584 | 3,978 | 5,652 |
| | Lighting | 36,270 | 68,709 | 96,811 | 120,367 | 139,140 | 24,017 | 45,655 | 64,554 | 80,539 | 93,300 |
| | Misc | 844 | 2,119 | 3,555 | 5,111 | 6,844 | 498 | 1,249 | 2,094 | 3,009 | 4,025 |
| | Motors | 1,025 | 2,811 | 5,162 | 8,076 | 11,627 | 757 | 2,076 | 3,811 | 5,961 | 8,583 |
| | Plug_Office | 688 | 1,729 | 2,898 | 4,163 | 5,569 | 412 | 1,033 | 1,731 | 2,485 | 3,322 |
| | Refrigeration | 3,656 | 7,261 | 10,680 | 13,658 | 16,469 | 2,941 | 5,842 | 8,599 | 10,983 | 13,242 |
| | WholeBldg | 5,770 | 14,117 | 23,648 | 34,006 | 46,370 | 4,226 | 10,442 | 17,624 | 25,470 | 34,957 |
| | **Total** | **52,739** | **106,667** | **158,679** | **207,862** | **255,572** | **36,292** | **73,806** | **110,350** | **145,164** | **179,209** |

*Table 8: C&I EE - Cumulative Savings by End-Use in EKPC Proposed Plan (MWh)*[48]



| | | Energy Savings (MWh) | | | | |
|---|---|---|---|---|---|---|
| End-Use | EKPC C&I EE Program | 2026 | 2027 | 2028 | 2029 | 2030 |
| Lighting | Commercial Advanced Lighting Program | 3,825 | 7,650 | 11,475 | 15,300 | 19,125 |
| HVAC | Commercial & Industrial Thermostat Program | 21 | 42 | 63 | 84 | 105 |

Reviewing those tables, it becomes apparent that EKPC is missing out on significant savings across all the categories with high potential for C&I customers as well. Even the programs that EKPC includes in its plan are far from ambitious compared to the achievable potential. Again, this indicates a need to ramp up existing programs, as well as introduce new ones. Programs targeting savings from lighting and HVAC equipment, although they are included in EKPC's plan, have projected savings that are significantly lacking compared to their MAP

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[47] SD-7, App. C.

[48] EKPC Resp. to JI Q2-55(g) at 8-9.

and RAP values. EKPC should also consider additional programs targeting whole building, motors, and refrigeration uses.

**Q. Does the EKPC proposed budget plan include all identified RAP potential for EE measures with relatively high winter season impacts?**

A. No. The EKPC plan for EE does not include any C&I heating measures (other than encouraging self-learning thermostats), motors, or industrial process measures, all of which can have substantial impacts on winter resource needs. Motors and industrial process loads typically have a flat load shape and would save energy all year, aligned with business hours of operation.

**Q. What is the expected cost of saved energy ($/kWh) for the C&I EE programs included in EKPC's plan?**

A. Both C&I EE programs have very low cost of energy saved. Increased incentives and program spending could significantly increase the expected savings. The Commercial Advanced Lighting Program has a high UCT score,[49] and the incentives provided could be significantly higher to increase participation. According to SD-3, free-riders are a consideration. Although free-rider estimates should be included in the projected costs, missing out on additional savings by increased participation to "minimize" free riders is not reasonable.

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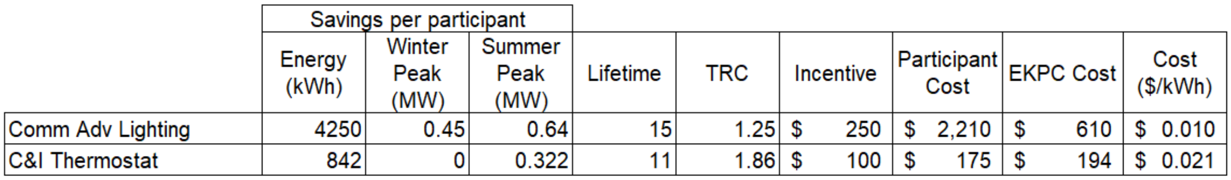
[49] Drake Direct at 17.

*Table 9: Impact and Cost Summary of C&I EE programs*[50]



| | Savings per participant | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Energy (kWh) | Winter Peak (MW) | Summer Peak (MW) | Lifetime | TRC | Incentive | Participant Cost | EKPC Cost | Cost ($/kWh) |
| Comm Adv Lighting | 4250 | 0.45 | 0.64 | 15 | 1.25 | $ 250 | $ 2,210 | $ 610 | $ 0.010 |
| C&I Thermostat | 842 | 0 | 0.322 | 11 | 1.86 | $ 100 | $ 175 | $ 194 | $ 0.021 |

**Q. What are your recommendations for the residential EE programs that should be included in the EKPC plan?**

A. EKPC should consider ramping up the two new C&I EE program offerings, examining increased incentives (especially for the lighting program) and overall spending. EKPC and its owner-members should also examine how to increase participation in the two programs through innovative program design. For example, Duke Energy Kentucky is offering the SmartPath program, which addresses savings from some of the leading end-uses, while also addressing cost barriers:[51]

> SmartPath is built upon the traditional Small Business Energy Saver option. It minimizes financial barriers to customer participation by allowing customers to finance and implement energy efficiency upgrades at little to no upfront costs. The program is implemented by a qualified Trade Ally network who complete[s] energy assessments, develops proposals, and implements the turnkey projects on the SmartPath option's behalf. SmartPath offers customers financing through a partnership with the National Energy Improvement Fund (NEIF). All financing is between the customer and NEIF and is offered by the Trade Allies.

Furthermore, EKPC should establish new programs targeting savings from heating, motors, and refrigeration uses, all of which can also deliver winter demand savings. Developing a custom C&I program offering would help to address this market segment given the heterogeneity of EKPC's owner-members' commercial customer base.

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[50] The table is based on information from Attach. SD-8, as well as Attach. JI 2-58. The cost is calculated based on the 2026 program spending (Attach. JI 2-58), and the estimated lifetime energy and demand savings for 2026 participants (Attach. SD-8).

[51] Case No. 2024-00352, Annual Status Report at ¶ 95.

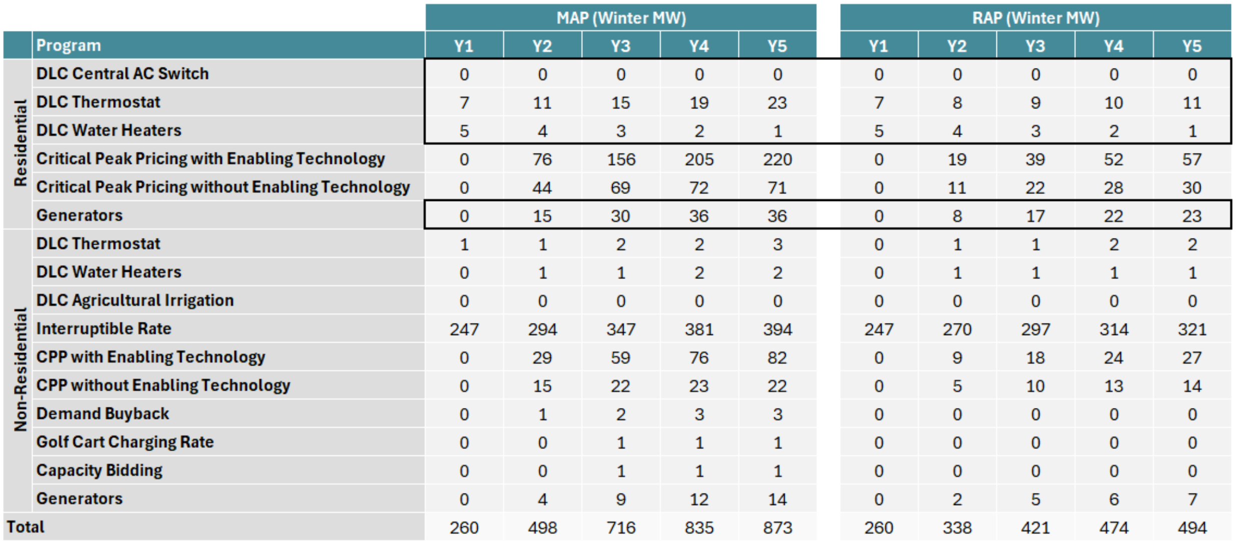
### B. EKPC's plan fails to pursue cost effective and achievable DR measures.

**Q. Please summarize your findings and recommendations with respect to the DR measures that EKPC includes in its plan.**

A. Yes.

- Tables 10 and 12 include the winter and summer demand RAP and MAP information for all DR measures examined in the Potential Study for a five-year period.
- Tables 11 and 13 include the annual winter and summer demand savings by program for all DR measures included in EKPC's DSM plan.

*Table 10: DR - Winter Annual MAP & RAP Savings by Program (MW)*[52]



| | | MAP (Winter MW) | | | | | RAP (Winter MW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Program** | **Y1** | **Y2** | **Y3** | **Y4** | **Y5** | **Y1** | **Y2** | **Y3** | **Y4** | **Y5** |
| **Residential** | **DLC Central AC Switch** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **DLC Thermostat** | 7 | 11 | 15 | 19 | 23 | 7 | 8 | 9 | 10 | 11 |
| | **DLC Water Heaters** | 5 | 4 | 3 | 2 | 1 | 5 | 4 | 3 | 2 | 1 |
| | **Critical Peak Pricing with Enabling Technology** | 0 | 76 | 156 | 205 | 220 | 0 | 19 | 39 | 52 | 57 |
| | **Critical Peak Pricing without Enabling Technology** | 0 | 44 | 69 | 72 | 71 | 0 | 11 | 22 | 28 | 30 |
| | **Generators** | 0 | 15 | 30 | 36 | 36 | 0 | 8 | 17 | 22 | 23 |
| **Non-Residential** | **DLC Thermostat** | 1 | 1 | 2 | 2 | 3 | 0 | 1 | 1 | 2 | 2 |
| | **DLC Water Heaters** | 0 | 1 | 1 | 2 | 2 | 0 | 1 | 1 | 1 | 1 |
| | **DLC Agricultural Irrigation** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **Interruptible Rate** | 247 | 294 | 347 | 381 | 394 | 247 | 270 | 297 | 314 | 321 |
| | **CPP with Enabling Technology** | 0 | 29 | 59 | 76 | 82 | 0 | 9 | 18 | 24 | 27 |
| | **CPP without Enabling Technology** | 0 | 15 | 22 | 23 | 22 | 0 | 5 | 10 | 13 | 14 |
| | **Demand Buyback** | 0 | 1 | 2 | 3 | 3 | 0 | 0 | 0 | 0 | 0 |
| | **Golf Cart Charging Rate** | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **Capacity Bidding** | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | **Generators** | 0 | 4 | 9 | 12 | 14 | 0 | 2 | 5 | 6 | 7 |
| **Total** | | 260 | 498 | 716 | 835 | 873 | 260 | 338 | 421 | 474 | 494 |

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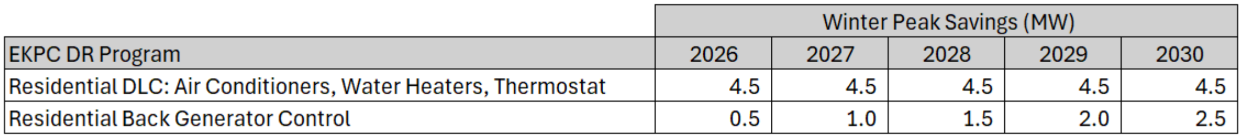
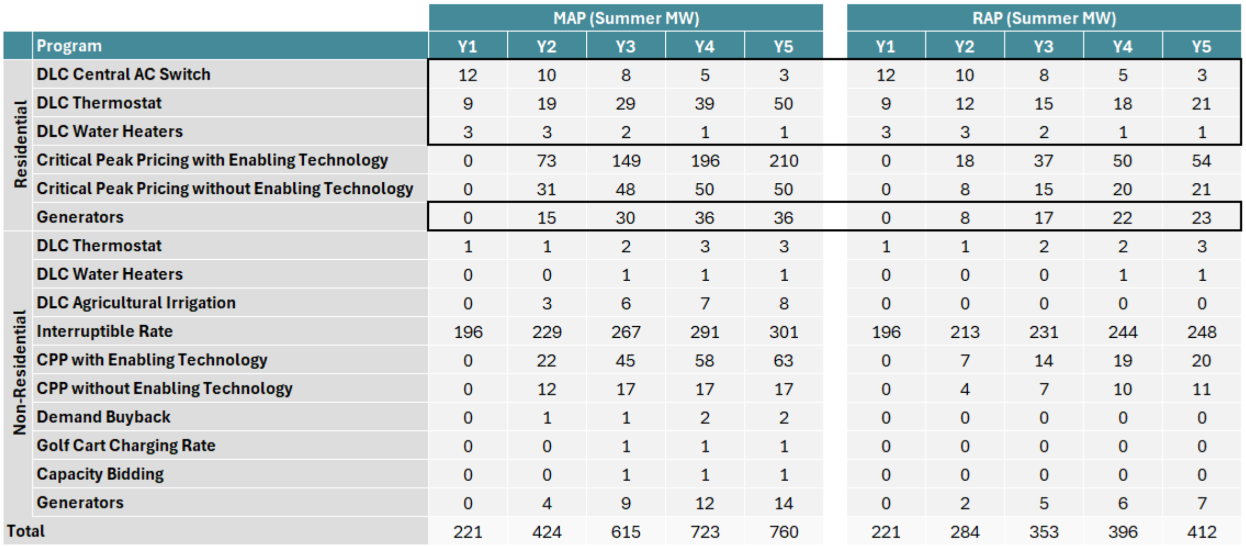
[52] SD-7, App. C.

*Table 11: DR - Winter Annual Savings by Program in EKPC Proposed Plan (MW)*[53]



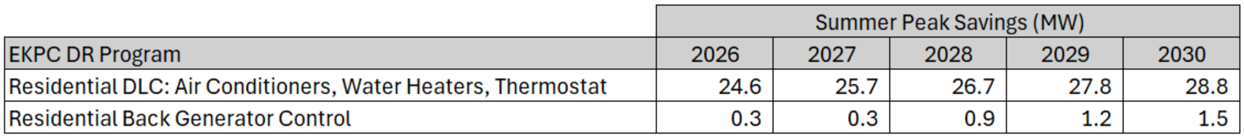
| | Winter Peak Savings (MW) | | | | |
|---|---|---|---|---|---|
| EKPC DR Program | 2026 | 2027 | 2028 | 2029 | 2030 |
| Residential DLC: Air Conditioners, Water Heaters, Thermostat | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Residential Back Generator Control | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 |

*Table 12: DR - Summer Annual MAP & RAP Savings by Program (MW)*



| | | MAP (Summer MW) | | | | | RAP (Summer MW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Program | Y1 | Y2 | Y3 | Y4 | Y5 | Y1 | Y2 | Y3 | Y4 | Y5 |
| Residential | DLC Central AC Switch | 12 | 10 | 8 | 5 | 3 | 12 | 10 | 8 | 5 | 3 |
| | DLC Thermostat | 9 | 19 | 29 | 39 | 50 | 9 | 12 | 15 | 18 | 21 |
| | DLC Water Heaters | 3 | 3 | 2 | 1 | 1 | 3 | 3 | 2 | 1 | 1 |
| | Critical Peak Pricing with Enabling Technology | 0 | 73 | 149 | 196 | 210 | 0 | 18 | 37 | 50 | 54 |
| | Critical Peak Pricing without Enabling Technology | 0 | 31 | 48 | 50 | 50 | 0 | 8 | 15 | 20 | 21 |
| | Generators | 0 | 15 | 30 | 36 | 36 | 0 | 8 | 17 | 22 | 23 |
| Non-Residential | DLC Thermostat | 1 | 1 | 2 | 3 | 3 | 1 | 1 | 2 | 2 | 3 |
| | DLC Water Heaters | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |
| | DLC Agricultural Irrigation | 0 | 3 | 6 | 7 | 8 | 0 | 0 | 0 | 0 | 0 |
| | Interruptible Rate | 196 | 229 | 267 | 291 | 301 | 196 | 213 | 231 | 244 | 248 |
| | CPP with Enabling Technology | 0 | 22 | 45 | 58 | 63 | 0 | 7 | 14 | 19 | 20 |
| | CPP without Enabling Technology | 0 | 12 | 17 | 17 | 17 | 0 | 4 | 7 | 10 | 11 |
| | Demand Buyback | 0 | 1 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 |
| | Golf Cart Charging Rate | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | Capacity Bidding | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | Generators | 0 | 4 | 9 | 12 | 14 | 0 | 2 | 5 | 6 | 7 |
| Total | | 221 | 424 | 615 | 723 | 760 | 221 | 284 | 353 | 396 | 412 |

*Table 13: DR - Summer Annual Savings by Program in EKPC Proposed Plan (MW)*[54],[55]



| | Summer Peak Savings (MW) | | | | |
|---|---|---|---|---|---|
| EKPC DR Program | 2026 | 2027 | 2028 | 2029 | 2030 |
| Residential DLC: Air Conditioners, Water Heaters, Thermostat | 24.6 | 25.7 | 26.7 | 27.8 | 28.8 |
| Residential Back Generator Control | 0.3 | 0.3 | 0.9 | 1.2 | 1.5 |

The largest DR measures for both the C&I and residential sectors based on the 2024 DSM Potential Study include Interruptible load. However, the application did not include a lot of information on EKPC's forward planning for interruptible load—other than that it currently has 200 MWs of interruptible load[56] and that it was included as an exogenous adjustment to

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[53] EKPC Resp. to JI Q2-55(g) at 10, 12.
[54] *Id.*
[55] DLC is an existing program and has participants from previous years. Without the two-year delay that I introduced for the RAP and MAP estimates of the Potential Study, the 2030 summer RAP would be 31 MW.
[56] Application at ¶ 2.

the load forecast.[57] The second largest DR measures and are pricing programs called Critical Peak Pricing ("CPP"), which account for a combined total of 106 MW of summer RAP and 127 MW of winter RAP within a five-year period. The respective MAP values are 339 MW (summer) and 396 MW (winter). Other notable savings opportunities are DLC of thermostats and water heaters, as well as the backup generators, which EKPC is planning to implement for residential customers. However, according to the 2024 Potential Study, significant additional savings are available for the residential backup generator program, while additional winter savings are available for the DLC program. Furthermore, savings for the same programs (DLC, generators) exist within the C&I class, which EKPC is not planning to pursue according to its filing.

**Q. Based on Tables 12 and 13, it seems that EKPC's DLC program is reaching the summer RAP. Is this correct?**

A. No. According to EKPC's response to Request JI Q2.67:

> EKPC informed the consultant performing the 2024 Potential Study that EKPC is not installing new water heater DLC switches at this time. The consultant did not model the residential DLC Water Heater MAP and RAP. The residential DLC Water Heater MAP and RAP should have been modeled even though EKPC is currently not pursuing new water heater DLC installations. This was a miscommunication between EKPC and the consultant.

Thus, there is additional potential that was not modeled (but should have) and that EKPC is not pursuing. According to the Application:[58]

> EKPC will not install new switches. All new enrollments will be Wi-Fi enabled thermostats provided by the end-use member under the "Bring Your Own Thermostat" (BYOT) option. Existing switches on air conditioners, heat pumps,

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[57] EKPC Resp. to JI Q2-65(c).
[58] Attach. JJT-2 at 31; Drake Direct at 32.

and water heaters will continue to be controlled and incentives for those units will continue to be paid for the life of the technology.

**Q. Why does the DLC program result in significantly lower savings in the winter as compared to the summer season?**

A. EKPC controls central air conditioners and heat pumps during extreme peak hours during the summer, but not during the winter. According to the EKPC DSM reports, "Although EKPC's system typically peaks in winter, member's heating appliances are not interrupted to lower peak. Member comfort and safety are top priority."[59] This results in significant missed demand savings in the season that EKPC most needs it. Although I understand that member comfort should be a top priority, this program design raises questions. Lowering (remotely) the thermostat set point during peak load conditions could relieve the system during critical events and reduce the probability of outages, while not materially impacting customers' comfort. The 2024 Potential Study recognizes that significant winter demand savings could be achieved through this program. According to Table 6-3, the winter savings would be similar to summer savings for DLC Thermostats (1.4 kW in winter for residential devices). Assuming 8,000 participants in 2025 and 1,000 new participants per year in the 2026-2030 period,[60] this would amount to 18.2 MW winter peak reduction by 2030.

**Q. What is the cost of demand saved ($/kW) of the DR programs included in EKPC's plan?**

A. Table 14 presents the load impacts of the DR resources and a summary of their costs.

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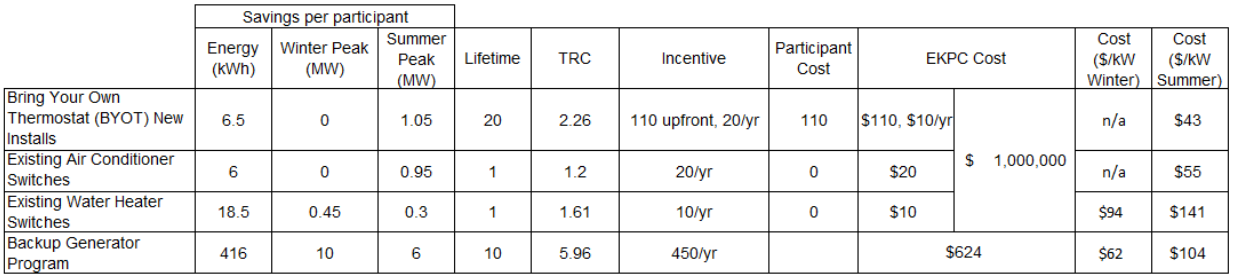
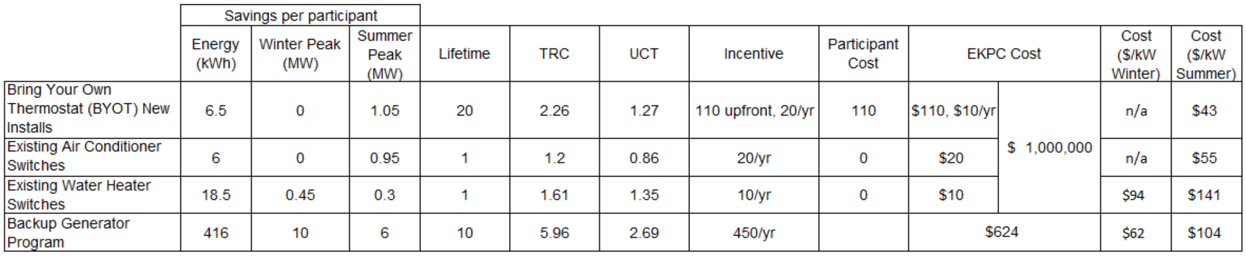
[59] Attach. SD-6 at 5.

[60] Attach. SD-8 ("Direct Load Control of Residential Air Conditioners and Heat Pumps: Bring Your Own Thermostat" page, "Participation" assumption).

*Table 14: Impact and Cost Summary of DR Programs*



| | Savings per participant | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy (kWh) | Winter Peak (MW) | Summer Peak (MW) | Lifetime | TRC | Incentive | Participant Cost | EKPC Cost | | Cost ($/kW Winter) | Cost ($/kW Summer) |
| Bring Your Own Thermostat (BYOT) New Installs | 6.5 | 0 | 1.05 | 20 | 2.26 | 110 upfront, 20/yr | 110 | $110, $10/yr | $ 1,000,000 | n/a | $43 |
| Existing Air Conditioner Switches | 6 | 0 | 0.95 | 1 | 1.2 | 20/yr | 0 | $20 | | n/a | $55 |
| Existing Water Heater Switches | 18.5 | 0.45 | 0.3 | 1 | 1.61 | 10/yr | 0 | $10 | | $94 | $141 |
| Backup Generator Program | 416 | 10 | 6 | 10 | 5.96 | 450/yr | | $624 | | $62 | $104 |



| | Savings per participant | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy (kWh) | Winter Peak (MW) | Summer Peak (MW) | Lifetime | TRC | UCT | Incentive | Participant Cost | EKPC Cost | | Cost ($/kW Winter) | Cost ($/kW Summer) |
| Bring Your Own Thermostat (BYOT) New Installs | 6.5 | 0 | 1.05 | 20 | 2.26 | 1.27 | 110 upfront, 20/yr | 110 | $110, $10/yr | $ 1,000,000 | n/a | $43 |
| Existing Air Conditioner Switches | 6 | 0 | 0.95 | 1 | 1.2 | 0.86 | 20/yr | 0 | $20 | | n/a | $55 |
| Existing Water Heater Switches | 18.5 | 0.45 | 0.3 | 1 | 1.61 | 1.35 | 10/yr | 0 | $10 | | $94 | $141 |
| Backup Generator Program | 416 | 10 | 6 | 10 | 5.96 | 2.69 | 450/yr | | $624 | | $62 | $104 |

**Q. What are your recommendations for the DR programs that should be included in the EKPC plan?**

A. EKPC should ramp up its current offerings by increasing the incentives offered and overall budget. The DLC program can be very attractive to end consumers, as it is not subject to high up-front costs. The design of the DLC program should be re-examined to capture winter peak savings. Furthermore, the same programs should be offered for C&I customers. Many C&I customers might already have backup generators that could participate in a program if available. Finally, the timing of winter peak (morning) coincides with work hours, so the heating load (and the potential relief) should be considered in designing a DLC program for C&I customers.

**Q. Have CPP programs been demonstrated to be successful in other jurisdictions at reducing peak demand?**

A. Yes. CPP pricing programs have been utilized by utilities all across the country and are subject to significant evaluation from independent third-party evaluators. A comprehensive study of utility pricing pilots, including CPP pilots with and without enabling technology, demonstrated that CPP can be effectively employed with customers to achieve significant reductions in peak energy use, with the majority of pilot impacts falling within 10% to 30% reductions in site electrical use.[61]

**Q. Other than the failure to include CPP in its program targets, do you have any other concerns about the price-based DR options included in EKPC's DSM Potential Study?**

A. Yes. EKPC did not include Time-of-Use ("TOU") rates as a source of potential peak load reductions.[62] Behavioral pricing programs like CPP and TOU are critical tools to manage the long-term energy demand. When customers are faced with a flat rate, they are not concerned with when they use electricity, which can cause significant misalignment with the market costs to generate and distribute power. By leveraging TOU rates, utilities can "shape" long-term demand patterns and encourage more off-peak consumption, thus allowing future supply-side resource additions to be better optimized and save costs.[63] Furthermore, there is a synergistic effect wherein TOU offered in combination with event-based DR notification can increase customer satisfaction and boost peak demand reductions by 6–11% for summer events, and 12% for winter events, compared to TOU only.[64]

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[61] *See* Ahmad Faruqui & Cecile Bourbonnais, *A Meta Analysis of Time-Varying Rates: The Arcturus Database*, Brattle Group (June 12, 2019), https://www.brattle.com/wp-content/uploads/2021/05/16560_a_meta_analysis_of_time-varying_rates.pdf. I interpreted the range of CPP impacts based on the figure on slide 4. You can see the top end of the range exceeds 50% of peak demand reduction, at 4.

[62] EKPC Resp. to JI Q2-75(b).

[63] Lawrence Berkeley Nat'l Lab., *2025 California Demand Response Potential Study – Charting California's Demand Response Future: Final Report on Phase 2 Results*, at 3-18, 5-55 (March 2017), https://eta-publications.lbl.gov/sites/default/files/lbnl-2001113.pdf.

[64] Cadmus, *Flex Pricing and Behavioral Demand Response Pilot Program Evaluation Report*, at 11 (pdf pg. 24), (Jun. 2018), https://edocs.puc.state.or.us/efdocs/HAH/um1708hah91734.pdf.

**Q. Does customer enrollment in TOU programs depend on factors such as the structure of the TOU rate and marketing?**

A. Yes. Designing a good TOU rate is critical to customer acceptance. Considerations such as the on- to off-peak price ratio can lead to significant differences in the amount of money customers could save, thereby changing the economic considerations for adopting the rate. Likewise, the length of the on-peak period will have implications for whether or not customers can shift their usage easily to the off-peak period. Finally, whether a rate has two or three periods and changes by season can affect customer acceptance. Ultimately, successful TOU programs require careful design and evaluation of customer experiences, but they are an important tool in shaping overall energy demand.

**Q. Have EKPC's member cooperatives implemented TOU programs and conducted evaluations?**

A. EKPC stated that some member cooperatives offer TOU programs either now or in the past, but they have seen low uptake.[65] Further, EKPC states that they have not performed any evaluations of the TOU programs that have been offered.[66]

I recommend that the Commission require EKPC to hire a third-party evaluator to conduct a process evaluation and feasibility study for implementing TOU and CPP rates across its member utilities, and to report findings within twelve months of issuing an order in this docket.

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[65] EKPC Resp. to JI Q2-75(b).

[66] EKPC Resp. to JI Q2-75(c).

### C. EKPC's plan misses significant peak savings that could result from Electric Vehicle ("EV") load management.

**Q. Does the EKPC plan include a program for EV load management?**

A. Yes. EKPC's plan includes a continuing program for EV load management. According to EKPC, "the Residential Electric Vehicle ('EV') Off-Peak Charging Program is designed to reduce the growth in peak demand resulting from the adoption of electric vehicles, thereby allowing EKPC to utilize its system more efficiently."[67] The program provides a monthly incentive for all registered EV charging energy (kWh) that occurs during the off-peak hours.

**Q. What are the expected impacts of the EV Off-Peak Charging Program?**

A. The program is not expected to result in energy savings as it does not reduce energy consumption but aims to shift it to off-peak hours. In the winter, the program is expected to reduce peak demand by 0.4 MW in 2030, while in the summer it can achieve higher savings equal to 2.5 MW of peak demand. The program assumes 500 new participants annually starting in 2026 (with the lifetime of savings being ten years).

**Q. What is the expected EV load in 2030 and how many EVs is EKPC projecting in the service territories of EKPC owner-members?**

A. The expected EV load in 2030 is 280 GWh.[68] EKPC assumes electricity consumption of 7,500 kWh per vehicle per year, an assumption that might be high.[69] Nevertheless, based on this assumption 37,333 EVs will be in the service territories of EKPC owner-members.

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[67] Drake Direct at 33.

[68] Attach. JJT-2 at 5.

[69] Using the average fuel efficiency of battery EVs of 3.6 mi/kWh and annual average vehicle miles traveled of 11,579 miles results in 3,216 kWh/yr. *See* U.S. Dept. of Energy, *Alternative Fuels Data Center: Data Sources and Assumptions for the Electricity Sources and Fuel-Cycle Emissions Tool*, https://afdc.energy.gov/vehicles/electric-emissions-sources (last visited Feb. 13, 2025).

**Q. What could the potential demand impact be if all EVs were to participate in the program?**

A. EKPC estimates per-vehicle savings of 1.65 kW in summer, and 0.29 in winter. Thus, the maximum savings if all vehicles were to participate would be 62 MW in the summer and 11 MW in the winter. These energy savings are cost-effective under the TRC test[70] and reflect substantial potential to manage future grid impacts stemming from vehicle electrification. Currently, the 2030 assumed enrollment of 2,500 vehicles in the program[71] represents only 7% of the total potential and should be increased.

**Q. What are your recommendations for the EV Off-Peak Charging Program?**

A. EKPC should continue offering this program to gain experience and understand how to best leverage the significant flexibility it can bring to the grid. EKPC should conduct a retrospective evaluation of the program, including rebates paid, actual kWh shifted from on- to off-peak, and customer motivations and satisfaction of the incentive level, in order to better inform future updates to the tariff. In future DSM plans, EKPC should further explore a charging program for commercial consumers. Given the morning peak during the winter, during work-hours, a commercial charging program might result in higher winter peak savings. Furthermore, EKPC should keep exploring EV load flexibility options including not

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[70] Attach. SD-9 at 10. I note that under the utility cost test (UCT), the Off-Peak EV Charging Program scored a 0.68. However, the same issue identified above regarding the possible over-estimation of annual kWh usage from an EV (7,500 kWh versus 3,216 kWh) impacts the UTC calculation based on the inclusion of utility rebates. These are identified as $140/yr based on an assumed 7,000 kWh per year of off-peak charging at $0.02/kWh incentive level. Therefore, a more accurate kWh usage estimate would potentially lower the costs of the program and increase the UCT score. See Attach. SD-8 for the rebate and usage assumptions used in the UCT calculation.

[71] EKPC response to JI 2-55 at 11.

only managed charging, but also bidirectional charging opportunities: vehicle-to-grid ("V2G")[72] or vehicle-to-building ("V2B") technologies.[73]

## VII. THE RAP LEVEL IDENTIFIED IN THE POTENTIAL STUDY UNDERESTIMATES THE REALISTICALLY ACHIEVABLE (AND ECONOMIC) SAVINGS AVAILABLE.

**Q. Based on your review, does the RAP level as estimated in the 2024 Potential Study capture all realistically achievable savings?**

A. No. The RAP, as identified in the Potential Study understates the savings that can be realistically achievable for two main reasons. First, it arbitrarily limits incentives to historical levels. Second, the Potential Study provides an extensive but not exhaustive list of options. A full range of potentially cost-effective incentive level and additional measures with savings potential need to be investigated. I discuss both issues in this Section. EKPC's reliance on past participation trends and program designs is not indicative of future potential adoption and should not limit EKPC's program offerings.

**Q. How does the Potential Study define RAP?**

A. As explained earlier, the RAP scenario estimates achievable potential with EKPC paying incentive levels (as a percentage of incremental measure costs) closely calibrated to historical levels.[74] To calculate RAP, the Potential Study first estimates the technical, economic, and achievable savings. Then the Study defines two scenarios, the MAP and RAP. Both scenarios reflect considerations around real-world barriers; the non-measure costs of delivering

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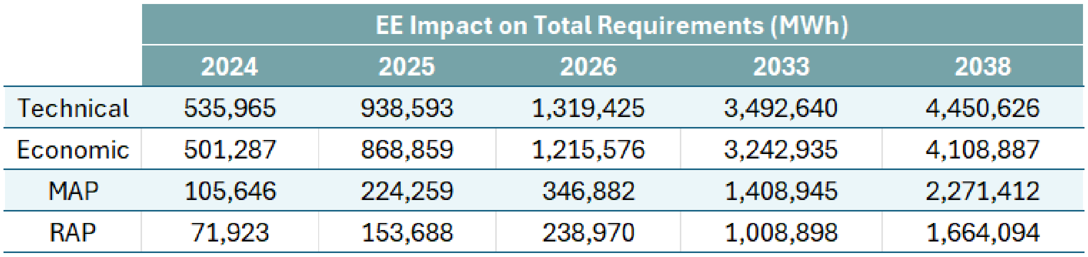
[72] "V2G" refers to bidirectional energy flow between an electric vehicle's battery and the charging station, allowing the EV to act as a battery.

[73] "V2B" refers to energy transferred to a building co-located with the charging station to manage the building's energy costs.

[74] Attach. SD-7 at 14.

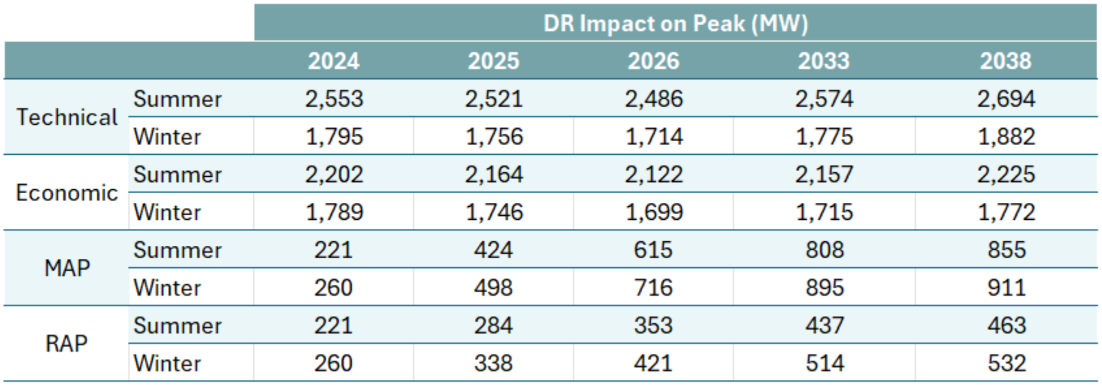
programs; and the capability of programs and administrators to boost program activity over time. The MAP estimates the potential savings assuming incentives equal to up to 100% of measure incremental costs. The RAP assumes incentives that are closely calibrated to historical levels. Thus, the RAP reflects a scenario in which EKPC chooses not to alter EE and DR incentive levels from historic norms. That is, however, an arbitrary constraint, and one that limits the ability to improve performance or credibly identify realistically achievable and cost-effective savings potential. On a going forward basis, incentive levels can and should be adjusted to maximize the level of cost-effective achievable savings. Tables 15 and 16 show the significant drop from the savings level that is characterized as economic (and would result in net savings for EKPC, its owner-member and their customers), the MAP, and the arbitrarily restricted RAP.

*Table 15: Technical, Economic, MAP, and RAP Energy Savings from EE (MWh)*[75]



| | EE Impact on Total Requirements (MWh) | | | | |
|---|---|---|---|---|---|
| | 2024 | 2025 | 2026 | 2033 | 2038 |
| Technical | 535,965 | 938,593 | 1,319,425 | 3,492,640 | 4,450,626 |
| Economic | 501,287 | 868,859 | 1,215,576 | 3,242,935 | 4,108,887 |
| MAP | 105,646 | 224,259 | 346,882 | 1,408,945 | 2,271,412 |
| RAP | 71,923 | 153,688 | 238,970 | 1,008,898 | 1,664,094 |

*Table 16: Technical, Economic, MAP, and RAP Peak Savings from DR (MW)*[76]



| | | DR Impact on Peak (MW) | | | | |
|---|---|---|---|---|---|---|
| | | 2024 | 2025 | 2026 | 2033 | 2038 |
| Technical | Summer | 2,553 | 2,521 | 2,486 | 2,574 | 2,694 |
| | Winter | 1,795 | 1,756 | 1,714 | 1,775 | 1,882 |
| Economic | Summer | 2,202 | 2,164 | 2,122 | 2,157 | 2,225 |
| | Winter | 1,789 | 1,746 | 1,699 | 1,715 | 1,772 |
| MAP | Summer | 221 | 424 | 615 | 808 | 855 |
| | Winter | 260 | 498 | 716 | 895 | 911 |
| RAP | Summer | 221 | 284 | 353 | 437 | 463 |
| | Winter | 260 | 338 | 421 | 514 | 532 |

**Q. What are the shortcomings of reliance on past customer acceptance of EE program offerings to inform selection of new or accelerated programs or measures?**

A. Past participation and customer feedback on potential new measures or programs do not give a complete picture as to possible future acceptance. This is due to the fact that new incentive levels can be much higher under the new avoided costs presented by EKPC, and customers may require higher rebates to overcome the challenges in enrolling in high upfront cost programs. Customers may apply an "implicit discount rate" to their own decision making that is orders of magnitude higher than the type of typical economic assumptions used to set incentive levels at a percentage of incremental cost, and calculate expected simple payback

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[75] Attach. SD-7, tbls.4-1 and 5-1.
[76] EKPC Resp. to JI Q2.66(a).

periods.[77] Indeed, primary research about barriers and motivations to adoption of energy efficiency programs in rural Iowa reinforces that the number one motivator for participation is economic, both in terms of potential cost savings and high up-front cost barriers.[78] Thus, putting an arbitrary cap on the most important motivator for participation in DSM programs is unreasonable and overly restrictive as EKPC aims to develop cost-effective resources.

**Q. Would significantly increased incentives lead to a material increase in the likelihood of customer enrollment in DSM programs?**

A. Yes. Although not the only factor customers consider when making a decision to participate in DSM programs, incentive levels are one of the top reasons customers choose to participate, or not, in a utility offering. By shortening the payback period,[79] greater incentive levels can motivate customers to participate in a program where they otherwise would not have. Research demonstrates the effectiveness of increasing incentives through the use of well-designed bonuses, which can spur higher savings levels, encourage customers to complete projects sooner than they would have otherwise, and increase project completion rates.[80] Tables 3-3 and 3-4 of the Potential Study show how increased incentives or shorter payback periods increase participation.

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[77] Monalisa Singh & Chandra Sekhar Bahinipati, *The Implicit Discount Rate, Information, and Investment in Energy-Efficient Appliances: A Review*, Ecology, Econ., and Soc'y–the INSEE J. 7(2), 11-28 (July 2024), https://ecoinsee.org/journal/ojs/index.php/ees/article/download/1021/319.

[78] Kara Gravert et al., *Homeowners' Motivations to Invest in Energy-Efficient and Renewable Energy Technologies in Rural Iowa*, Multidiscip. J. Civ. Eng. 2(1), at 6, 10(2024), https://ascelibrary.org/doi/pdf/10.1061/AOMJAH.AOENG-0010.

[79] The "payback period" refers to the amount of time it takes for the cost savings from the reduction in energy bills to offset the initial customer investment.

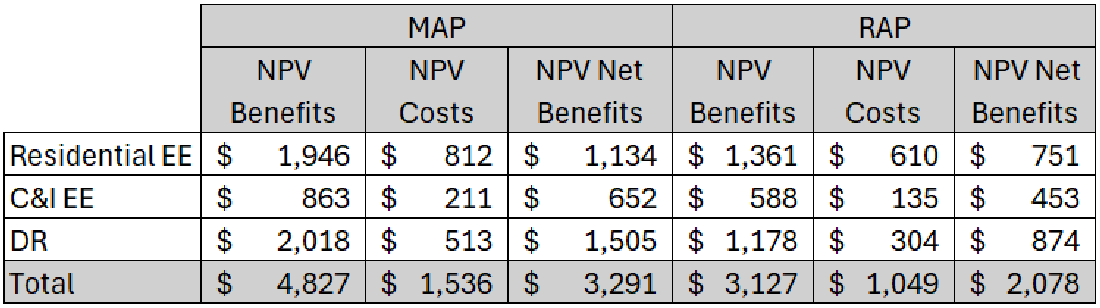
[80] Jackie Goss et al., *Turning on a Dime: Using Bonus Incentives to Influence Project Completion*, ACEEE Summer Study on Energy Efficiency in Industry, at 4-5 (2015), https://www.aceee.org/files/proceedings/2015/data/papers/6-183.pdf.

**Q. Would increasing incentives above historical levels result in programs that are not cost-effective?**

A. No. Depending on the program and measure, there can be more or less headroom to increase incentives while maintaining cost-effectiveness. For instance, according to EKPC, the Heat Pump Retrofit Program has Utility Cost Test ("UCT") scores that range from 2.6 to 5.92.[81] This means that program incentive budgets could be increased by up to two or five times their current level for the respective measure and the programs would still yield benefits greater than or equal to their costs -- even if no new participants were assumed.[82] Realistically however, an increase in incentive levels would likely increase participation and resulting savings levels (i.e., MW and MWh reductions).

**Q. According to the Potential Study, increasing incentives from historical levels to 100% of the incremental cost of the DSM measure, would increase net savings more than $1 billion by 2038 in Net Present Value ("NPV") as illustrated in Table 17.[83]**

*Table 1: Cost Savings from RAP and MAP by 2038 ($M)*



| | MAP | | | RAP | | |
|---|---|---|---|---|---|---|
| | NPV Benefits | NPV Costs | NPV Net Benefits | NPV Benefits | NPV Costs | NPV Net Benefits |
| Residential EE | $ 1,946 | $ 812 | $ 1,134 | $ 1,361 | $ 610 | $ 751 |
| C&I EE | $ 863 | $ 211 | $ 652 | $ 588 | $ 135 | $ 453 |
| DR | $ 2,018 | $ 513 | $ 1,505 | $ 1,178 | $ 304 | $ 874 |
| Total | $ 4,827 | $ 1,536 | $ 3,291 | $ 3,127 | $ 1,049 | $ 2,078 |

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[81] Drake Direct at 17.

[82] Incentives are part of the utility costs in the UCT test. Administration (program overhead) costs are also included. For example, with a UTC score higher than 2, if the incentive doubles, the UCT will still be higher or equal to 1 depending on the level of administration costs.

[83] Attach. SD-7, tbls.4-4, 5-4, 6-12.

**Q. Would new program design and delivery approaches provide additional ways to overcome past barriers to participation, given the rural nature of EKPC's member cooperative base?**

A. Yes. There are many examples of innovative program design to overcome persistent barriers to participation of rural communities in EE program offerings and achieve greater energy savings. A study highlighting the "rural efficiency gap" identified these barriers facing rural communities and finds the top barriers to be in three broad categories:[84]

- Geographic barriers: these barriers stem from the physical distance of rural communities from more dense population centers, and the subsequent challenges these can bring in reaching economies of scale for service delivery. Workforce availability to perform the upgrades is listed as another key challenge related to geographic isolation.
- Financial barriers: these barriers relate to the high upfront cost of energy efficiency, coupled with the lower median incomes of rural households. In addition, difficulties to accessing credit, or an aversion to taking on debt to finance efficiency, can pose substantial barriers.
- Awareness and access barriers: these barriers stem from factors such as the lack of access to online marketing due to relative lack of broadband internet access, and potential lack of awareness and general skepticism toward efficiency resources.

The study recommends many strategies to "bridge the gap" and I discuss some examples later in my testimony related to specific recommendations.

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[84] Brooks Winner et al., *Bridging the Rural Efficiency Gap: Expanding access to energy efficiency upgrades in remote and high energy cost communities*, Island Institute, at 4-5 (2018), https://www.islandinstitute.org/wp-content/uploads/2021/03/Bridging-the-Rural-Efficiency-Gap-final-report.pdf.

**Q. Are there any examples of programs that have successfully increased adoption and overcome these barriers for rural utilities?**

A. Yes. The Pay As You Save® or PAYS® program model is a trademark offering developed by the Energy Efficiency Institute, and is free to use by program implementers if they follow certain minimum program requirements meant to protect customers, lower barriers to participation in on-bill financing offerings, and ensure utility system benefits.[85] PAYS® is an example of a special energy efficiency financing tool called inclusive utility investments,[86] where customers participate in a program and face no up-front cost (which is the number one barrier to increased participation) and the utility recovers the cost of the project on the utility bill through a specialized tariff.[87] Studies have shown how some customers do not like traditional on-bill financing options which are implemented more like a typical consumer loan, and customers may be risk-averse, have low credit scores, or have a general attitude and belief against taking on personal financing. These barriers were specifically addressed with the design of PAYS®, which features significant consumer protections and guarantees such as minimum cash savings guarantees.[88] PAYS® has been deployed by an EE implementer (EEtility), with approved tariffs in many rural utility service areas including Missouri, Georgia, and Arkansas.[89] A review of five PAYS® program case studies revealed that

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[85] Southeast Energy Efficiency Alliance, *Utility Guide to Tariffed On-Bill Programs*, at 3 (2020), https://www.seealliance.org/wp-content/uploads/SEEA_TOBGuide_FINAL_UPDATED_2020_04_13.pdf.
[86] The ENERGYSTAR® website provides an overview of inclusive utility investments, available at https://www.energystar.gov/products/inclusive_utility_investment.
[87] *See id.* at 3-4; Energy Efficiency Inst., Inc., *PAYS® Essential Elements & Minimum Program Requirements* , (updated July 20, 2021), http://www.eeivt.com/pays-essential-elements-minimum-program-requirements-2/.
[88] Homes Hummel & Harlan Lachman, ACEEE, *What Is Inclusive Financing for Energy Efficiency, and Why Are Some of the Largest States in the Country Calling for it Now?*, at 13-14, 13-17, 13-18 (2018), https://www.aceee.org/files/proceedings/2018/assets/attachments/0194_0286_000158.pdf. Another critical feature is that under the PAYS® model, the loan does not move with you if you were to move residences. The loan stays with the meter and therefore reduces customer concerns about additional debt obligations should they move.
[89] EEtility Co., *Everyone Saves with PAYS®*, https://www.eetility.com/pays a (last visited Feb. 12, 2025).

customers can save on average 15% of their annual electricity usage.[90] In Arkansas, Ouachita Electric Cooperative credited its PAYS® efficiency program as a key contributor to a 4.5% decrease in rates, after serving 10% of its residential customers over three years, with average monthly bill savings just above $16 per customer.[91]

**Q. Has EKPC previously offered a program similar to the PAYS® model?**

A. Yes, at a small scale, EKPC's Kentucky Energy Retrofit Rider, originally (How$mart Kentucky) was initially authorized by the Commission as a pilot in 2010, and approved as a permanent tariff offering in 2013.[92] The Kentucky Energy Retrofit Rider enabled inclusive utility investment programs through owner-member cooperatives. Mountain Association worked with 6 cooperatives to pioneer program implementation, with investments of more than $2.5 million for 325 retrofits to date, with a cost recovery rate of 99.5%.

With greater EKPC support to expand the Kentucky Energy Retrofit Rider program to more owner-member cooperatives and more participants, there could be greater uptake of efficiency measures with bill savings for participants and system-wide benefits. I recommend that EKPC investigate barriers to adoption for other owner-members and develop additional resources to help scale this program, such as providing supplemental financing options, workforce training opportunities, and administrative capabilities.

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[90] Jeff Deason et al., Lawrence Berkeley Nat'l Lab, *Customer outcomes in Pay-As-You-Save programs*, at 3, 16 (Aug.2022), https://eta-publications.lbl.gov/sites/default/files/deason_aceee_2022_preprint.pdf.

[91] Nat'l Rural Utils. Coop. Finance Corp. News, *Solar + Efficiency + Innovation = Lower Rates for Arkansas Co-op Members* (Dec. 16, 2019), https://www.nrucfc.coop/content/nrucfc/en/news/stories/solar---efficiency---innovation---lower-rates-for-arkansas-co-op.html.

[92] Order, *In the Matter of Joint Application of Big Sandy Rural Electric Cooperative Corp., Fleming-Mason Energy Cooperative, Inc., and Grayson Rural Electric Cooperative Corp. for an Order Approving Ky Energy Retrofit Rider Permanent Tariff*, Case No. 2012-00484, at 1-2, 8-9 (Aug. 26, 2013), https://psc.ky.gov/pscscf/2012%20Cases/2012-00484/20130826_PSC_ORDER.pdf.

### A. The Potential Study did not consider all available program designs and delivery channels.

1. <u>EKPC does not include distributed solar and storage in its resource mix.</u>

**Q. Did EKPC include future distributed solar PV adoption in its load forecast, or include a study on distributed PV potential as a possible tool to lower the resource need?**

A. No. EKPC did not include a forecast of solar PV in its load forecast, and, to my knowledge, did not conduct a study of distributed solar PV potential. According to an independent forecast conducted for the Kentucky Energy Office, the long-term potential for distributed solar PV ranges from 13 to 603 MW-dc nameplate capacity[93] by 2040 across EKPC cooperative service areas, with a mid-case scenario of 327 MW-dc.[94] The amount of annual energy produced from the mid-case scenario of PV adoption is 430,000 MWh.[95] Including distributed battery storage in its portfolio would increase the ability to use store the solar output, especially in winter, and align with peak time periods.

**Q. Are distributed solar and storage systems critical elements of a resilient and low-cost electric system resource mix?**

A. Yes. Due to the significant price declines over the past decade solar energy is very competitive on a levelized cost of energy basis and should be a key feature of any forward-

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[93] According to the U.S. Energy Information Administration, "(n)ameplate generator capacity is determined by the generator's manufacturer and indicates the maximum output of electricity a generator can produce without exceeding design thermal limits." U.S. Energy Info. Admin., *Frequently Asked Questions (FAQs): What is the difference between electricity generation capacity and electricity generation?* (last updated Feb. 6, 2024), https://www.eia.gov/tools/faqs/faq.php?id=101&t=3.https://www.eia.gov/tools/faqs/faq.php?id=101&t=3.

[94] Pieter Gagnon & Paritosh Das, *Projections of Distributed Photovoltaic Adoption in Kentucky through 2040*, National Renewable Energy Laboratory, at 15 (June 2017), https://www.nrel.gov/docs/fy17osti/68656.pdf.

[95] Based on simulating the monthly production profile of a 327 MW-dc solar resource in central Kentucky using the online software PV Watts, there would be approximately 433,000 MWh per year of solar generation with 100,000 MWh of this annual energy production that falls in the winter months of November through February. Nat'l Renewable Energy Lab., *PV Watts Calculator®: Solar Resource Data*, https://pvwatts.nrel.gov/pvwatts.php (last visited Feb. 12, 2025).

looking resource plan. When storage is added to the resource mix, flexibility within the system increases, and if the storage is located behind the customer meter or close to load on the distribution system, you can have added resilience to outages. Further, when coupled together there is a synergistic effect, as demonstrated in a study that found 42% demand charge reduction for commercial customers from paired solar and storage, compared to 8% for solar PV by itself and 23% reduction for storage by itself.[96]

**Q. Did EKPC evaluate the use of distributed energy storage to meet its capacity needs?**

A. No. EKPC stated that they did not include non-residential battery storage in their evaluation of potential DSM measures,[97] and further indicated that they left both battery electric storage and thermal storage systems out of their DR plan because they were not cost effective.[98]

**Q. Would solar and storage be a viable option for EKPC, given the rural customer base of its members?**

A. Yes. The National Rural Electric Cooperative highlights the use of battery storage in microgrids among rural cooperatives, demonstrating that this is a viable option for the type of customer base that EKPC serves. For example, the Rose Acre Farms Microgrid project in rural North Carolina features a microgrid with a 2 MW solar array and a 2.5 MW / 5 MWh battery storage system.[99] Working with rural farmers to investigate the co-benefits of

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[96] John Shenot et al., *Capturing More Value from Combinations of PV and Other Distributed Energy Resources*, National Renewable Energy Laboratory (2024), https://www.nrel.gov/docs/fy24osti/90129.pdf.
[97] EKPC Resp. to J QI2-75.
[98] EKPC Resp. to J QI2-57(b).
[99] Cooperative, *Rural Energy Storage Deployment Program (RESDP)*, https://www.cooperative.com/programs-services/bts/Rural-Energy-Storage-Deployment-Program/Pages/default.aspx (last visited Feb. 12, 2025).

agrivoltaics[100] could lead to a significant source of new solar PV potential while also yielding much-needed additional revenue streams for the farmers. In addition, research by agricultural extension and engineering researchers at Oregon State University finds that "converting just 1% of U.S. farmland to agrivoltaics could meet the nation's renewable energy targets."[101]

2. <u>EKPC should investigate new financing and program delivery strategies to better serve manufactured housing and investigate other emerging technologies to serve increasing demand.</u>

**Q. What kinds of challenges do manufactured homes present to electric cooperatives in terms of their energy and demand impacts?**

A. According to the National Rural Electric Cooperative Association ("NRECA"), manufactured homes are prevalent in rural cooperatives' service areas and are typically made up of older units with less efficient equipment, compared to newer homes. Furthermore, because manufactured homes are more likely to be all-electric, this means that they often have inefficient electric resistance space and water heating, which causes excessive peak demand spikes in addition to wasting significant amounts of energy per year.[102]

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[100] "Agrivoltaics" refers to the incorporation of solar photovoltaics into agricultural production systems, as opposed to viewing them as competing for the same land. Studies have demonstrated the synergistic effects not just on solar PV output (due to lower cell temperatures from being near crops), but also on crop and livestock yields due to the partial shading provided by the solar arrays.

[101] *See* Sean Nealon, *Crops and kilowatts: Agrivoltaics project will harvest solar energy from farmland*, Oregon State University (Feb. 2, 2023), https://engineering.oregonstate.edu/all-stories/crops-and-killowatts-agrivoltaics-project-will-harvest-solar-energy-farmland.

[102] Katherine Dayem, *Business & Technology Surveillance: Today's Best Opportunities for Improving Manufactured Homes Efficiency*, NRECA, at 3,6 (July 2019), https://www.cooperative.com/programs-services/bts/Documents/TechSurveillance/Surveillance-Manufactured-Housing-Efficiency-July-2019.pdf ("because most manufactured homes use electric space heating and air conditioning, inefficient HVAC systems and building envelopes drive up load and contribute significantly to co-op demand peaks . . . . Not surprisingly, the electric load of manufactured home heating contributes significantly to peak demand.").

**Q. Does EKPC have DSM program offerings that manufactured homes are eligible for?**

A. Yes. EKPC's residential Touchstone Energy Home program provides incentives to home builders to make new homes 25% more efficient than the code required minimum.[103] Manufactured homes are eligible for this program; however, this program only addresses new homes which are already required by code to be highly efficient. In addition, manufactured homes would be eligible for weatherization incentives through the Button-Up Weatherization program, as well as individual equipment incentives offered through the Heat Pump Retrofit program, the High Efficiency Heat Pump program, and the CARES low-income program.

**Q. Do manufactured homes face specific challenges that the existing program designs and offerings may fail to maximize?**

A. Yes, potentially. Although it is good to have a wide variety of program offerings for which manufactured homes are eligible, this alone may not be enough to overcome the substantial barriers faced by this housing type and encourage deep energy savings. Research conducted for the design of a new manufactured home replacement program in Michigan finds that "(o)lder manufactured homes can be difficult to weatherize, and in some situations, it may be more economical and better for the residents' health, to replace the home rather than try to repair it."[104] In addition, program offerings tailored specifically to manufactured homes can help account for some of their unique features, such as the unique duct layout in these structures, common points of failure, and the challenges associated with contractors working

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[103] Drake Direct at 10.

[104] Shannon Stendel, & Rachel Krogman, *Great Lakes Energy Manufactured Home Replacement Research*, Slipstream, at 1 (Jan. 24, 2023), https://slipstreaminc.org/sites/default/files/documents/publications/great-lakes-manufactured-home-replacement-final-report1.pdf.

in the underbelly of the home.[105] For these reasons developing strategies that go beyond relying solely on existing broadly applicable residential rebates (i.e., those that are designed and applicable across site-built single family homes, multifamily homes, and manufactured homes) may be preferable to reach the full DSM potential for this market segment.

**Q. Are there examples of successful program designs to upgrade or replace older Manufactured Homes in rural areas that EKPC should consider?**

A. Yes. Energy Trust of Oregon has piloted a successful Manufactured Home Replacement Program that was turned into a regular program offering[106] and was recognized by the State Legislature as an imperative tool to address the many combined challenges facing rural communities.[107] Umatilla Electric Cooperative in Oregon also offers a manufactured home replacement program to its rural customer base that blends together multiple different types of funding.[108] In Louisiana, Entergy began offering a manufactured housing retrofit program in 2018 and has retrofitted more than 1,200 manufactured homes since its inception.[109] Innovative designs in program delivery can help overcome many obstacles leading to the "rural efficiency gap" outlined above, such as forming community partnerships, combining forces and resources, and developing innovative financing.[110] We recommend that the Commission require EKPC to file a pilot proposal for a Manufactured Home Replacement

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[105] Aimee Bell-Pasht, *Topic Briefs: Upgrading Manufactured Homes*, ACEEE, at 3 (Aug. 2023), https://www.aceee.org/sites/default/files/pdfs/topic_briefs_-_upgrading_manufactured_homes_links_fixed.pdf.

[106] Energy Trust of Oregon, *Find Comfort in a More Efficient Home* (Aug. 2024), https://www.energytrust.org/wp-content/uploads/2024/09/Manufactured_Home-Replacement_FLY_08_2024.pdf.

[107] Or. Rev. Stat. § 458.356(2).

[108] *See:* Umatilla Elec. Coop. Bus. Res. Ctr., *Manufactured Home Replacement Program*, https://www.uecbrc.com/general-8 (last visited Feb. 13, 2025).

[109] Aimee Bell-Pasht, *supra* note 105, at 5.

[110] Brooks Winner et al., *supra* note 84, at 5-6, 27-29.

Pilot that seeks to overcome persistent barriers to adoption of energy efficiency measures in this market segment.

3. <u>EKPC should explore emerging technologies in future DSM plans.</u>

**Q. Are there any other emerging technologies that EKPC should consider when developing future DSM Plans?**

A. Yes. I am including with my testimony the below referenced Exhibits that showcase promising breakthrough technologies that can add significant benefit to rural Kentuckians. I recommend that the Commission require EKPC to include treatment of emerging technology in future DSM Potential Studies, including but not limited to the types of technologies and program delivery mechanisms in the Exhibits below. I further recommend the Commission require EKPC to conduct a feasibility study to implement these emerging technologies as a pilot program offering and technology demonstration that can increase confidence of its member-cooperatives.

- Exhibit MR-2: Industrial Heat Pumps: Electrifying Industry's Process Heat Supply (ACEEE).
- Exhibit MR-3: Field Study of Ground Source Integrated Heat Pump – Final Report (Oak Ridge National Laboratory).
- Exhibit MR-4: Manufactured Home Replacement Program – Pilot Evaluation (Energy Trust of Oregon / Opinion Dynamics Corporation)
- Exhibit MR-5: A New State of the Art: Zero Energy Modular Multifamily Construction (VEIC)

- Exhibit MR-6: Zero Energy Modular Factory Initiative (VEIC)

## VIII. RECOMMENDATIONS AND CONCLUSION

**Q. Please summarize your recommendations.**

A. I recommend that the Commission:

- Approve the proposed DSM Plan for program years 2025, 2026, and 2027, with immediate modifications:
  - Extend the plan's budget to at least $11.4 million (reflecting the High scenario developed in the 2024 Potential Study), ensuring that programs are available to more customers.
  - Modify the Demand Load Control ("DLC") Bring Your Own Thermostat ("BYOT") program to allow for winter peak reduction.
  - Offer the DLC and Back-up generator programs to Commercial & Industrial ("C&I") customers.
  - Increase the incentives provided for all residential programs, especially those of shell programs.
- Order EKPC to develop, within six months of a final order in this proceeding, an updated DSM Plan proposal that will aggressively pursue all realistically achievable DSM programs as identified in the 2024 Potential Study.
  - The proposal should pursue at least the RAP savings as projected in the 2024 Potential Study, namely 400,000 MWh of energy efficiency and winter peak demand reductions of 173 MW by 2030.[111]
  - Explore additional programs that at minimum include:
    - Residential and Commercial Energy Assessments and programs targeting behavioral changes.
    - Additional Residential programs targeting inefficient electric heating, and water heating equipment.
    - Programs tailored for manufactured housing.
    - New Commercial programs targeting savings from heating, motors, and refrigeration uses, all of which can also deliver winter demand savings.

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[111] Note that Table 2, below, shows the basis for these energy and demand targets.

        - Non-residential EV charging plans.
    - Explore financing opportunities and new program designs in line with national best practices to overcome persistent barriers to participation, e.g., Pay-As-You-Save Program ("PAYS®") model, also referred to as on-bill financing ("OBF") or Inclusive Utility Investment ("IUI") programs, to overcome high upfront cost barriers.
    - Evaluate the impact of increasing incentives for programs including, at minimum, the following programs:
        - DLC;
        - Commercial Advanced Lighting;
        - All residential heating, ventilation, and air conditioning ("HVAC") equipment and shell programs.
- Order EKPC to provide, within twelve months of a final order in this proceeding, an updated Potential Study or other serious analysis correcting for the flaws and shortcomings identified here to provide more accurate estimates of cost-effective, achievable potential. The updated analysis should include at least the following adjustments:
    - Determination of optimal incentives that aim to maximize energy and cost savings, without over-relying on unjustified limits on incentive and/or spending levels.
    - The assessment of the potential of distributed solar and energy storage resources.
    - The assessment of emerging technologies, including but not limited to bidirectional charging, and the types of technologies and program delivery mechanisms in the Exhibits MR-2, MR-3, MR-4, MR-5.
    - Together with the Potential Study, EKPC should provide a third-party process evaluation and feasibility study for implementing Time-of-Use ("TOU") and Critical Peak Pricing ("CPP") rates across its member utilities.
- Order EKPC to propose, by no later than Jan. 2027, an updated DSM Plan that will utilize and observe the updated potential study to pursue re-assessed achievable programs and include additional programs and measures recommended. That updated DSM Plan should also propose guidelines for the stakeholder collaborative process as well as EKPC's (and owner-members') in-house evaluation of the Potential Study findings in the development of the proposed DSM plan. Guidelines should ensure a transparent process and outline evaluation criteria for programs, design principles, and documentation of process and results (including program elimination or rejection decisions).

- Direct EKPC to perform integrated analysis of DSM potential on equal footing with supply-side resources in all future resource planning, including but not limited to Integrated Resource Plan (“IRP”) and Certificate of Public Convenience and Necessity (“CPCN”) proceedings. This should include allowing DSM resources to be a selectable resource together with supply-side resources in resource optimization modeling.

**Q. Does this conclude your testimony?**

A. Yes.

# VERIFICATION

The undersigned, Maria Roumpani, being first duly sworn, deposes and says that she has personal knowledge of the matters set forth in the foregoing testimony and that the information contained therein is true and correct to the best of her information, knowledge, and belief, after reasonable inquiry.

Maria Roumpani
______________________________

Subscribed and sworn to before me by Maria Roumpani, this 13th day of February, 2025.

RISA BRANA
Notary Public - State of Florida
Commission # HH501559
Expires on April 12, 2028

______________________________
Notary Public Risa Brana

State of Florida
County of Miami-Dade

___ Personally Known OR [✓ ___ Produced Identification]

Type of Identification Produced __PASSPORT

My commission expires: 04/12/2028

Notarized remotely online using communication technology via Proof.

EXHIBIT MR-1

# Maria Roumpani

*Partner,* mroumpani@currentenergy.group

## Professional Summary

Maria is an expert in energy system planning and an energy modeler. She focuses on the economic and technical analysis of grid planning and operations issues and has experience in capacity expansion optimization, production cost simulations, and energy storage dispatch modeling. Maria has submitted expert testimony and comments on integrated resource planning, plant economics, unit commitment practices, and power cost issues and her clients include consumer advocates, public interest organizations, energy project developers, government agencies, and large energy buyers.

## Education

**PhD, Management Science & Engineering**
Stanford University, 2018

**MSc, Electrical and Computer Engineering**
National Technical University of Athens, 2009

## Work Experience

**Founding Partner, Current Energy Group, (May 2024 – Present)**

- Founding partner specializing in the economic and technical analysis of grid planning and operations issues, including capacity expansion, production cost, and energy storage dispatch modeling.

**Founder, ELO Engineering Consulting (March 2024 – May 2024)**

- Energy policy and economic issues.

**Technical Director | Strategen Consulting (2018 – March 2024)**

- Led firmwide technical and economic modeling and analysis to support consulting engagements. Specialized in the use of modeling tools to inform grid planning and decarbonization issues.

**Research Assistant | Precourt Institute for Energy, Stanford University (2011 – 2017)**

- Conducted research in a wide range of topics, from game theoretical approaches in electricity markets to behavioral economics.

**Researcher | Energy, Economics, & Environment Modeling laboratory, National Technical University of Athens, (2009-2010, 2015)**

- Contributed to the development of mathematical models:
- Capacity expansion of electricity supply
- Wholesale electricity market competition model

# Expert Testimony

NV Energy and Sierra Pacific Power Company 2025-2044 Integrated Resource Plan
on behalf of Advanced Energy United
Public Utilities Commission of Nevada
Docket No. 24-05041
Testimony

Duke Energy Carolinas and Duke Energy Progress 2023 Integrated Resource Plans
on behalf of Sierra Club, South Carolina Coastal Conservation League, Southern Alliance for Clean Energy, Upstate Forever, and Vote Solar
Public Service Commission of South Carolina
Docket No. 2023-8-E & No. 2023-10-E
Testimony

Biennial Consolidated Carbon Plan and Integrated Resource Plans of Duke Energy Carolinas, and Duke Energy Progress,
on behalf of the Southern Alliance for Clean Energy, Sierra Club, Natural Resources Defense Council, and North Carolina Sustainable Energy Association
North Carolina Utilities Commission
Docket E-100, Sub 190
Testimony

Annual Review of Base Rates for Fuel Costs of Dominion Energy South Carolina, Inc.
on behalf of the South Carolina Office of Regulatory Staff
Public Service Commission of South Carolina
Docket No 2023-2-E
Testimony

Annual Review of Base Rates for Fuel Costs of Duke Energy Progress, LLC
on behalf of the South Carolina Office of Regulatory Staff
Public Service Commission of South Carolina
Docket No 2023-1-E
Testimony

Virginia Electric and Power Company 2023 IRP
on behalf of Advanced Energy United
Virginia State Corporation Commission
Case No. PUR-2023-00066
Testimony

PacifiCorp's Transition Adjustment Mechanism
Oregon Public Utilities Commission
Docket No. UE 420
Testimony

DTE 2022 IRP
on behalf of the Michigan Energy Innovation Business Council
Michigan Public Service Commission
Case U-21193
Testimony

Duke Energy Carolinas and Duke Energy Progress 2022 Carbon Plan
on behalf of the Tech Customers
North Carolina Utilities Commission
Docket E-100, Sub 179
Testimony

Public Service Company of Colorado
on behalf of Sierra Club
Colorado Public Utilities Commission
Proceeding No. 21A-0141E
Testimony

EXHIBIT MR-2

# INDUSTRIAL HEAT PUMPS: ELECTRIFYING INDUSTRY'S PROCESS HEAT SUPPLY

**Ed Rightor, Paul Scheihing,**
**Andrew Hoffmeister,**
**Riyaz Papar**

**March 2022**
**ACEEE Report**

# Contents

# About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

# About the Authors

**Edward Rightor** is the director of ACEEE's industrial program. He develops strategic vision for industry, shapes the research and policy agenda, and convenes stakeholders to advance energy efficiency. Prior to joining ACEEE, Ed held several leadership roles at Dow Chemical during his 31-year career. He holds three patents. He earned a PhD in chemistry from Michigan State University and a bachelor of science in chemistry from Marietta College.

**Paul Scheihing** is principal of 50001 Strategies LLC, where he provides industrial energy efficiency and energy management expertise. He previously worked within the U.S. Department of Energy Advanced Manufacturing Office for 30 years and was the lead on the Superior Energy Performance program. He has also managed many other RD&D programs including DOE's Industrial Heat Pump program from 1988 to 1995. For this report, Paul provided technical expertise on IHP technology.

**Andrew Hoffmeister** is a program analyst on ACEEE's industrial team. His work focuses primarily on decarbonization policy research, messaging, and outreach. Prior to joining ACEEE, Andrew volunteered with the Tennessee Department of Environment and Conservation on its watershed project in the Cumberland River Basin and researched decarbonization planning. He holds a bachelor's degree in earth and environmental science from Vanderbilt University.

**Riyaz Papar** is CEO of C2A Sustainable Solutions, LLC and has 30 years of industrial thermal system optimization field experience. He is a registered professional engineer (ME), certified energy manager, and a Fellow of ASME and ASHRAE. He has worked on several industrial energy efficiency projects in both the United States and internationally with the U.S. DOE and UNIDO. Riyaz has a master's (ME) from the University of Maryland and a bachelor's (ME) from the Indian Institute of Technology – Mumbai.

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# Executive Summary

## KEY FINDINGS

- Industrial heat pumps (IHPs) can save up to 32% of the source energy for process heat generation. For industrial groups such as food, chemicals, and pulp and paper, our work shows IHPs could save the energy equivalent to powering 1.3 million homes and $CO_2$ emissions equivalent to that of 2.7 million passenger cars.
- IHPs can have simple economic paybacks under two years in states where the price of electricity is advantaged over that of natural gas. Yet, due to uncertainties about full implementation capital costs, integration, and maintenance, incentives from policy and utilities are essential for accelerating adoption—especially in most states where the electricity/natural gas cost ratio is disadvantaged.
- Field-level demonstrations of various IHP types—in multiple industrial applications—are crucial to lowering hurdles, increasing awareness of IHP benefits, and developing diverse workforce to support installations. Broad support and engagement across industry, utilities, agencies, and technology providers is needed to promptly accelerate demonstrations and the learning they provide.

Industry accounts for more than 25% of the nation's energy use and energy-related carbon dioxide ($CO_2$) emissions—emissions that must be reduced to achieve national and international climate goals. Among climate stabilization experts, decarbonization, that is, dramatically reducing atmospheric net GHG emissions and decoupling energy and feedstock use from fossil fuels, is a widely accepted goal.

Industry has several pathways to decarbonization, including electrification; today, it gets 17.6% of its total site energy and less than 5% of its process heating energy from electricity. Instead, U.S. industry sources most of its energy from fossil fuels—largely natural gas. This energy includes process heat: The heat that powers manufacturing and accounts for 50% of on-site industrial energy use. There are thousands of industrial operations, and with process heat being cross-cutting, electrifying it using low-carbon sources is a prime opportunity. Here, industrial heat pumps (IHPs) can significantly reduce energy consumption and GHGs while aiding electrification by providing much of the process heat needed in U.S. industry and helping to make dramatic cuts in industrial emissions.

Currently, a few types of IHPs can provide heat up to about 160°C (covering roughly 44% of industrial process heat needs), and products are in development to raise this temperature ceiling to about 200°C (covering roughly 55% of industrial process heat needs). IHPs are not new. They were integrated into U.S. industrial processes to a limited extent as far back as the 1960s and have been referred to as mechanical or thermal vapor recompression (MVR, TVR) units. The arrival of inexpensive natural gas cut into their economic favorability, and adoption stalled. Today, their use is sparse and their capabilities for energy- and GHG-reduction remain largely unknown. Now, the urgency of the climate crisis and advancements in IHP technology (e.g., doubling the maximum temperature to 160°C for several IHP types), make them a key industrial electrification solution.

Increasing corporate interest in both sustainability and GHG reductions are strong arguments for implementing IHPs without delay. And we can do this now with the right incentives and policy levers. The high price of electricity relative to the low price of natural gas is the largest economic obstacle to IHP adoption. Our research shows that IHPs can have paybacks under two years (an attractive marker), especially when the electricity/natural gas price ratio is under 4. In regions of the country where this ratio is over 4, policies can have a key role in addressing this economic gap. Other hurdles include process integration, uncertainties (e.g., service lifetime, maintenance), product availability, and workforce limitations (e.g., lack of experienced and trained process engineers).

Policymakers can address these uncertainties with economic incentives and support for development of a skilled workforce; such efforts will have the added benefit of creating jobs. Expanding pilot and demonstration projects will help convince industrial-sector leaders of IHP viability and benefits over current equipment. IHPs are being aggressively deployed in Europe, Japan, and Australia, and the manufacturers are primarily in the European Union and Japan. There are no suppliers in the United States (above 0.5 megawatts), so global suppliers need to be incentivized to pilot IHPs while a domestic market is still being developed.

Our research shows that moderate deployment of IHPs in industrial groups with high process heating demands, such as pulp and paper, chemicals, and food manufacturing, could save 26–32% of the source energy (or 166–210 trillion Btus net depending on scenario after subtracting electricity use) across multiple unit operations, which is the equivalent energy use/year of 1.1–1.3 million homes. In parallel, IHPs could avoid emissions of 9.7–12.6 million metric tons/year of $CO_2$, equivalent to emissions from 2.1–2.7 million passenger cars. As the electric supply becomes further decarbonized, the amount of $CO_2$ avoided could double. The electricity used to run the IHPs (instead of natural gas) would approach 2.1 gigawatts of electricity: the power needed to run several medium sized cities. Expansion of IHP use across the far greater breadth of industry would save even more energy and $CO_2$ emissions.

Our report goes beyond high-level assessments and describes how and where IHPs could be deployed at the unit operations level (the basic process level where materials are transformed, separated, and dried). The following unit operations in three industrial groups were analyzed.

**Paper:** pulp mill digester and multi-effect evaporator; non-integrated paper mill pulper

**Food:** wet corn-milling steepwater and high fructose corn syrup starch conversion; potato-processing hot air dryer

**Chemicals:** ethyl alcohol for fuel applications from dry mill production, ethylene (above ambient) debutanizer reboiler, and process water stripper reboiler.

This report shows how and where IHPs could deliver energy and GHG savings while delivering multiple nonenergy benefits like cleaner air, improved temperature control, productivity, quality, and waste reduction. The report also describes routes that stakeholders can use to lower hurdles, enable policy, and develop public-private partnerships that accelerate adoption.

# Definitions/Acronyms

| Acronym | Definition |
|---|---|
| AMO | Advanced Manufacturing Office |
| BASF | Badische Anilin und Soda Fabrik, leading chemical manufacturer |
| Btu | British thermal unit |
| CapEx | Capital cost |
| Cwt | Hundred weight |
| $CO_2e$ | Carbon dioxide equivalent |
| COP | Coefficient of performance |
| Cts | cents |
| DOE | Department of Energy |
| GHG | Greenhouse gases |
| GJ | Gigajoule units |
| GWP | Global warming potential |
| HA | Heat activated |
| IHP | Industrial heat pump |
| kW | Kilowatt |
| kWh | Kilowatt hour |
| MMBtus | Millions of British thermal units |
| MT | Metric ton |
| MMT | Millions of metric tons |
| MVC | Mechanical vapor compression |
| MVR | Mechanical vapor recompression |
| MW | Megawatt |

| | |
|---|---|
| NYSERDA | New York State Energy Research & Development Authority |
| PB | Payback |
| PSIG | Pounds per square inch gauge |
| RD&D | Research, development, and deployment |
| TBtus | Trillions of British thermal units |
| TVR | Thermal vapor recompression |
| WCM | Wet corn milling |

# Introduction

Industry accounts for more than 25% of the nation's energy use[1] and energy-related carbon dioxide ($CO_2$) emissions. Considering the magnitude of its emissions and its role in supplying goods that enable reductions in other sectors, industry is an increasing focus of the societal drive for climate stabilization. U.S. industry's generation and use of process heat, 7,576 trillion Btus/year (EIA 2021a), accounts for 51% of on-site industrial energy use and thus is a prime target for energy and $CO_2$ emissions reduction.

Among climate stabilization experts, decarbonization[2]—replacing fossil fuels with power from low-carbon sources like wind, solar, and hydropower—is a widely accepted goal. Beneficial electrification (Whitlock, Elliott, and Rightor 2020), where fossil fuel use is replaced with electricity from low-carbon sources, stands out as a key pathway to making step-change reductions in this footprint as the grid is decarbonized. The potential for electrification to transform the footprint of process heat is high, as electricity accounts for only 5% of this heat today, with the balance from fossil fuels.

Industrial heat pumps (IHPs) are a key technology that can be scaled as part of the transformation of industry's process heat generation. IHPs are not new: There was increased IHP commercialization in Europe from 1995–2010 (IEA, Annex 48). IHPs had been integrated into U.S. industrial processes to a limited extent as far back as the 1960s, when they were known as mechanical or thermal vapor recompression (MVR, TVR) units (Gluckman and McMullan 1988), but the production of inexpensive natural gas in the United States reduced their economic advantage and adoption stalled. Today, their use is sparse and their capabilities for energy and GHG reduction are largely unknown. Now, the urgency of the climate crisis and advancements in IHP technology (they can now produce heat 80°C higher than their previous maximum temperature, reaching 160°C for some IHPs), make them a logical solution to cutting industrial GHG emissions.

IHPs can reduce industry's carbon footprint in several ways: 1) electrification of process heat; 2) improved efficiency: current generation IHPs use power more efficiently and can be deployed locally, avoiding lengthy steam distributions systems; and 3) reuse or recovery of waste heat. These approaches are interrelated; they depend on how much of the process heat load is electrified and on the carbon intensity of the electricity; the degree of GHG reduction may vary. Regardless of the source of the waste heat (fossil fuel, biomass, solar, or nuclear) recovering and upgrading waste heat is valuable for many applications. Corporate

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[1] Including feedstocks—fossil inputs to material production (i.e., plastics, chemicals)

[2] In this report decarbonization will refer to reducing atmospheric net GHG emissions (in terms of $CO_2$ equivalents ($CO_2e$)) attributable to industrial processes.

appetite for sustainable energy and GHG reduction is a strong motivation for upgrading and effectively using process heat, including implementing IHPs, without delay.

The low price of natural gas compared to electricity is currently the largest economic obstacle to IHP adoption. In many cases, however, IHPs have paybacks that are acceptable to industry, especially in regions of the country where the electricity/natural gas price ratio is under 4. Other obstacles include the uncertainty of investing in newer IHPs that are not yet widely adopted, and long equipment lifetimes (>15 years) providing infrequent opportunities for equipment replacement. Policymakers can minimize perceived risk through economic incentives and by supporting the development of a workforce skilled at designing, installing, and servicing IHPs (with the added benefit of creating jobs). Policies have a key role to play in accelerating adoption.

While there have been multiple studies examining the potential for IHPs in some industries, there are no recent studies that examine actual process heating and cooling streams to determine IHP potential; there is a paucity of IHP applications information for specific industries and processes at the energy analysis level.

The research in this report aims to fill this gap by providing information at the unit operations level. This report presents research examining the IHP market; capability fit with industrial needs; economics; electrification potential to reduce energy and GHGs; and enablers to accelerate research, development, and deployment (RD&D) of current and emerging IHP technologies in U.S. industry. The technical nature of this report lays the foundation for gauging where IHPs can most effectively provide process heat in industry and connects to policies that could accelerate adoption.

# Background

Multiple drivers are revitalizing interest in addressing the energy and carbon footprint of process heat within the United States, including more aggressive company GHG reduction/sustainability goals, industry consideration of electrification of process heat demand, and nonenergy benefits, such as improved process control, faster temperature adjustments, reduced water consumption for cooling, and local heat generation versus centralized steam systems.

## PROCESS HEAT AND THERMAL RANGES OF INTEREST

Industrial subsectors with high levels of process heating demand in the supply (i.e., heat pump sink) temperature range are shown in figure 1. Process heat is used in numerous applications that are common across these industry groups, including (in order of the amount of energy consumed): fluid heating and distillation, drying, metal smelting, and calcing (DOE 2015). The temperature range of 60–200°C is an attractive range for IHPs. Currently, a few types of IHPs can provide heat up to about 160°C (covering roughly 44% of industrial process heat needs), and further developments may raise this temperature ceiling to about 200°C (covering roughly 55% of industrial process heat needs). Where refrigeration is present (e.g., food and some chemical applications), dual heating and cooling service would also be an ideal market entry for IHPs in the United States (EIA 2021a).

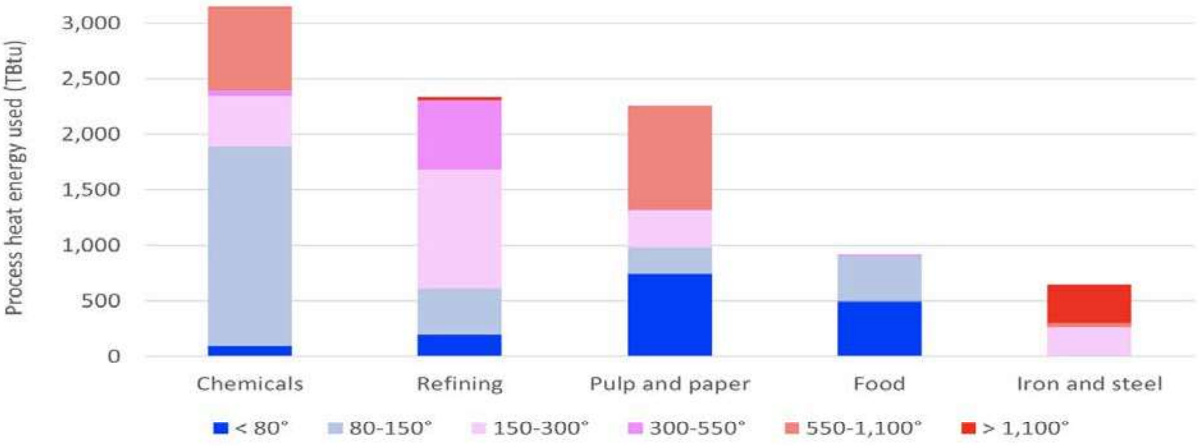

**Figure 1. Process heat demand at different temperature (°C) levels in select U.S. Industrial l groups. Data source: McMillan 2019.**

Where process cooling and heating are both significant (e.g., breweries, wineries, food processing, some chemical and material processing), dedicated heat recovery chillers (a form of IHP) can offset significant fossil fuel use for steam generation while improving efficiency and reducing costs (Rightor, Whitlock, and Elliott 2020). In addition to replacements for steam generation (Bless et al. 2017; Arpagaus 2020a), IHPs are being considered for drying products and removing water from solids, which accounts for 15–25% of the energy associated with processes (Jakobs 2019). Applications for moisture removal are numerous and include proofing bread dough, manufacturing bricks, purifying chemical products, and drying biosolids.

## INDUSTRIAL HEAT PUMPS

At their simplest, heat pumps are devices that move heat from low to high temperature, often using a vapor compression system similar to the heat pump space heating systems used in homes and buildings or in refrigerators. However, industrial heat pumps are more complicated, tailored to meet the diverse needs of industrial processes, and they are usually integrated with one or more such processes.

Prior studies showed that moderate deployment of IHPs in manufacturing could save 2–5% of the total U.S. industrial process heat demand (170–350 trillion Btus/year) and avoid emissions of 12–25 million tons/year of $CO_2$ by 2010 (IEA 1995). IHPs are used commercially in numerous industrial applications globally, yet adoption of earlier generation IHPs in the United States was limited due to a relatively low upper temperature bound for conventional heat pumps (80°C, primarily due to limitations of refrigerants and other working fluids), the high cost of electricity versus natural gas in some regions of North America, compressor technology limitations, and the lack of field service capabilities.

Mechanical and thermal vapor recompression IHPs (e.g., MVRs, TVRs) can be found in industry. A survey of the industrial use of IHPs in 1988 found 69 closed cycle and 309 open cycle IHPs in use (excluding lumber drying) (Gluckman and McMullan 1988). The closed cycle IHPs were largely used in water/sewer facilities with fewer units in food, chemicals, and dairy. The open cycles were found in dairy, wet corn milling, chemicals, water/sewer, and pulp and paper. The later Annex 21 study found 318 IHPs in use, with the estimated percentage of plants with IHPs ranging from 1–5%, with the exception of corn milling, which had 20% (Annex 21).

An updated survey of IHP use in industry would be advantageous. When we interviewed industry leaders, we heard that scattered MVRs and TVRs are operating in dairy, corn milling, liquor, and pulp and paper applications but their number is relatively low. We did learn that IHPs can be found in equipment provided as a package, such as drying equipment, concentrators, and multi-effect evaporators. Advances in low-environmental-impact refrigerants (McLinden et al. 2014) and other working fluids (oils and other lubricants specially designed for IHP applications) that can operate at higher delivery temperatures (e.g., up to 160°C for electrically driven IHPs) have broadened the range of IHP applications, such as in waste heat recovery and product drying, which can account for 12–25% of energy use (Lauermann et al. 2019).

As the technology has advanced, so has understanding of IHP economics and favorable deployment scenarios (Arpagaus and Bertsch 2020; Arpagaus 2020a; Kosmadakis et al. 2020). Further, new heat activated IHP technologies, driven mostly by waste heat, promise to supply process heat up to 260°C. Also, the potential of more favorable economics (high heat pump lift temperature, e.g., 80 K) compared to electric-driven vapor compression heat pumps could provide even broader applicability (QPinch 2021).

The market and vendor capabilities for IHPs are most well developed in Europe and Japan (Arpagaus et al. 2018), where there are strong economic (relatively high fuel-to-electricity utility rates) and policy incentives (e.g., European carbon price and/or mandated carbon targets), and well-funded public-private R&D partnerships to develop IHP technology (e.g., the Horizon Europe program or Japan New Energy and Industrial Technology Development Organization (NEDO) to decarbonize and electrify process heating demand. IHPs are commercially available today, and there are hundreds of economic applications that have been documented with case studies (IEA Annex 48). A recent study of the IHP potential in Europe highlighted that 80% of the IHPs in industry would be under 5 MW, meaning that the vast majority of IHP applications are within reach of modest commercial systems under this upper scale marker.  (Marina et al. 2021). (Here MW refers to the heating capacity or heat pump thermal output and not the electrical power supplied to the heat pump). Recent IHP demonstrations include those at 1–2 MW (Borealis 2021), again showing application of this technology within a reachable range. Also, IHPs were mentioned in BASF's goals of reducing $CO_2$ 25% by 2030 and getting to net zero $CO_2$ by 2050 (BASF 2021).

## TYPES OF INDUSTRIAL HEAT PUMPS

There are multiple types of IHPs. For example, ambient heat pumps can work as stand-alone equipment for relatively low temperature uses such as preheating and heating air and water. Heat activated heat pumps rely on prime heat or waste heat to drive them and are installed near an existing base process where there is excess heat that can be used. IHPs can be open cycle, where the heat pump working fluid is the process stream itself, such as when waste steam is being compressed and returns for process, or closed cycle, where the heat pump has a heat exchange on the heat source and sink side to separate the heat pump working fluid from the environment. A classification of IHPs is provided in figure 2. Six IHP types were considered in this work for optimum fit within any process; they are briefly described below, and more detail is provided in table A2 of Appendix A. These descriptions are illustrative of process types and not meant to be comprehensive.

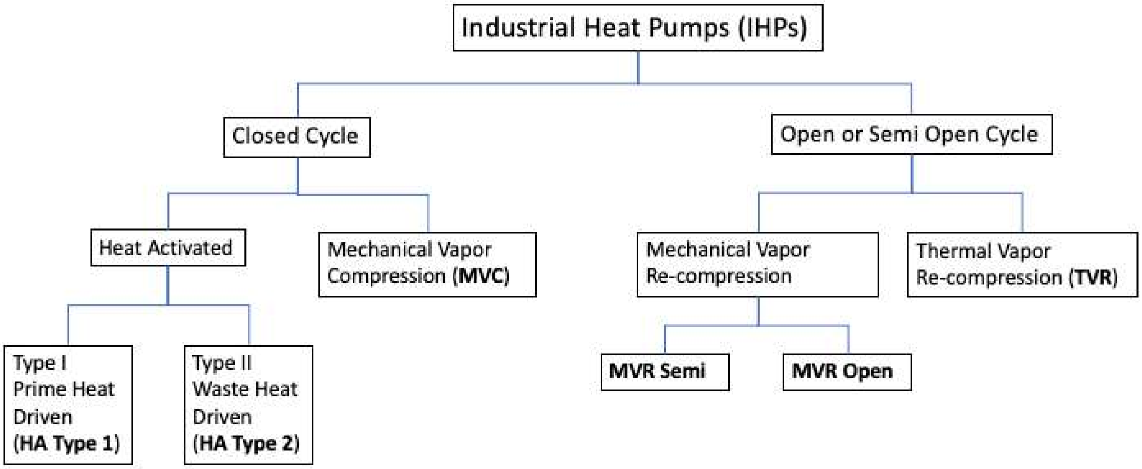

Figure 2. Six different IHP types considered in this study (adapted from Gluckman and McMullan 1988)

The IHPs are introduced below; detailed descriptions can be found in Appendix A. Parameters for the economic estimates, including capital costs and maintenance cost factors, can be found in Appendix B and table B1. The choice of IHP type depends on the application and multiple parameters. For the unit operations examined in this study, insights on IHP types are provided in the "Types and Fit with Applications" section.

1. Mechanical vapor compression (MVC), closed cycle. A completely closed refrigerant loop maintains the working fluid's pressures and temperatures. A heat exchanger is required on both the heat sink (condenser) and heat source (evaporator) sides.
2. Mechanical vapor recompression (MVR Semi), semi-open cycle. This IHP will typically take advantage of recompressing waste low-pressure steam or hydrocarbon vapor that would otherwise be vented or condensed with heat rejected to the ambient air.

3. Mechanical vapor recompression (MVR Open), open cycle. The difference between the semi-open and open cycle is that a heat exchanger is used in the semi-open cycle to keep the waste vapors separate from the process steam or other heat exchange process vapors/liquids. In the open cycle, the (waste) vapors are reinjected directly back into the process without a separate heat exchanger.
4. Thermal vapor recompression (TVR), open cycle. The TVR heat pump is perhaps the most common in industry today. It is the simplest as it has no moving parts, but it is restricted to compressing low-pressure (waste) steam (heat source) to a medium pressure steam header (heat sink) using high-pressure steam (IHP driver). It does not use any electrical energy. Additional information on TVRs and their efficiency can be found in Appendix D.
5. Heat activated Type 1 (HA Type 1), closed cycle. The heat activated (HA) heat pump technology uses various chemical processes, such as absorption, adsorption, or a reversible chemical reaction to transfer the heat from the source to the sink. In these systems the heat pump cycle is predominantly heat activated. However, it does require a small amount of electricity for pumping the working fluids. The Type 1 design requires a supply of prime heat at an elevated temperature well above the heat sink temperature to enable it to lift the waste heat to the intermediate sink temperature.
6. Heat activated Type 2 (HA Type 2), closed cycle. The Type 2 design is a waste-heat-driven heat pump where typically about one unit of heat is lifted to the higher sink temperature and one unit of heat is rejected to the ambient temperature. Type 2 designs require a sufficient temperature difference between the heat source and ambient, relative to the heat sink and source (lift temperature). Additional information on the efficiency assumptions HA IHPs can be found in Appendix D.

# Methodology Summary

This section describes why we chose certain industrial groups and unit operations for study. It also explains how we decided on where to place the IHPs in the thermal cascade associated with these processes (e.g., pinch analysis), and it notes the process used to validate parameters, assumptions, and early results. The pinch analyses were crucial to optimize the efficient upgrading of thermal energy while minimizing the energy spend. They provide a starting assessment useful for discussion with experts at the plant level. For this study the pinch analyses also were central to providing outputs for estimation of energy and GHG reduction potential at the unit operations level, as well as simple economic assessments. It should be noted that detailed engineering, thermal, integration, and economic studies would be needed to advance pilot or final implementation.

## CHOICE OF MARKET APPLICATIONS

The food, paper, and chemicals industry groups were chosen for study as they have a high proportion of low-moderate process heat in a temperature range (e.g., 60–200°C) that is readily accessible by IHPs. Food unit operations tend to be less highly integrated, and their simplicity was attractive. Food as well as pulp and paper facilities can found throughout the United States, providing good representation for dispersed industries. Chemicals applications, as well as pulp and paper, can have high to moderate levels of process heat integration, representing more complex systems. Evaporation and drying (areas of likely IHP applicability) are common in all of these industrial groups. The industrial groups and unit operations selected for study are summarized in table 1.

The Annex 21 study (IEA 1995) examined 24 top candidate applications. A related study described the IHP impact potential (RCG/Hagler Bailey, Inc. 1995). Research on IHPs in the United States has been largely dormant since these studies, but they provided a good starting point for exploring candidate processes in our study.

It should be noted that the North American Industry Classification System (NAICS) codes are used in this report to reference the portions of industry analyzed. For the NAICS code, the first two numbers designate the sector, the third the subsector, the fourth the industry group, the fifth the industry, and the sixth number the national industry. For some of the entities examined, data could not be assigned to a single NAICS code (e.g., potato processing, ethylene) so data at the industry group level were used as a starting point and assumptions were made based on public industry information that could be found.

**Table 1. NAICS codes for industries of interest for this work**

| Manufacturing sectors | Select subsector | Select industry group | Industry |
|---|---|---|---|
| 31 | Food (311) | Fruit and vegetables (3114) | Wet corn milling (311221) |
| 32 | Pulp and paper (322)<br>Chemicals (325) | | Pulp mills (322110)<br>Paper mills (322121)<br>Newsprint (322122)<br>Paperboard mills (322130)<br>Petrochemicals (325110)<br>Ethyl alcohol (325193) |

## PINCH ANALYSIS

We used pinch analysis to find the optimum location for the IHP in the multiple thermal flows typical of industrial processes. The optimum location where the heat availability (heat sources) is best aligned with the heat demands (heat sinks) is called the "pinch point." Pinch analysis is a structured methodology for minimizing the energy consumption of industrial processes by optimizing process operations including heat recovery systems and energy supply. In the past 40 years, application of this methodology in multiple industrial segments has been able to identify savings in energy (10–35%), water consumption (25–40%), and hydrogen consumption (up to 20%) (NRCan 2003). In production facilities that have been highly optimized for heat integration (e.g., world scale chemical plants), the potential savings may be smaller.

The pinch analysis identified the best cold streams (heat sinks) and hot streams (heat sources) for the heat pump to operate between (source to sink), including the size of the source and sink (MMBtus/ton product) and the temperature range of the source and sink. Careful attention was paid for getting hot or cold streams that were best suited for heat pumping by, for example, minimizing the number of hot or cold streams (one is ideal), evaporating and condensing streams, and lifting the temperature required by the heat pump. Details on the pinch analysis can be found in Appendix G with a more detailed description in the Annex, section 1. An explanation of the IChemE software used for pinch analyses is given in the Annex, section 2. We used data from earlier studies graciously provided by Per-Ake Franck of Chalmers ETA (Sweden) as a starting point for these analyses.[3] Finally, the Annex, sections 3, 4, and 5 document the inputs and assumptions, raw data, and results for all nine unit operations analyzed.

To most effectively apply the IHPs, we screened for the conditions summarized in table 2.

**Table 2. Screening criteria for IHP applications.**

| Parameter | Maximum, with emerging technology | Ideal target today |
|---|---|---|
| Process heat sink temperature | < 200°C | < 160°C |
| Lift temperature | < 100°C | < 40°C |
| Heat sources and sinks comparable in size (MW) | Multiple condensing or evaporating streams at constant temperature with multiple hot and cold streams with temperature glide | One condensing or evaporating application at constant temperature and the other with hot or cold stream with glide |

The ideally placed and integrated IHP would take heat from a heat source around 5°C or more below the pinch point and pump or upgrade the heat to a desired "lift" to the heat sink, around 5°C or more above the pinch point. If done efficiently, heat exchangers could be minimized, particularly above the pinch point. Figure 3 shows an IHP lifting heat by capturing waste heat at $T_{source}$ and delivering heat to the process heat load at $T_{sink}$. The higher the IHP lift temperature, the greater the IHP capital cost and required IHP driver

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[3] Franck, Per-Ake, Chalmers E-Sectionens Teletekniska Avdelnining (ETA), Pinch Analysis of Hot and Cold Stream Data for 140 Industrial Processes, pers. comm., December 2020.

energy and the lower the IHP coefficient of performance (COP); see also Appendix A, table A1 for definitions of COP for the various IHP types.

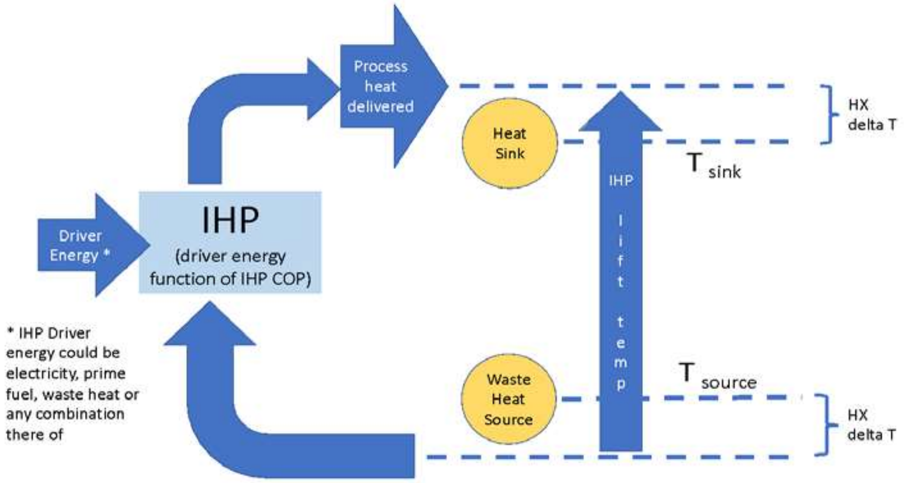

Figure 3. Generic IHP diagram illustrating IHP lift temperature, $T_{source}$ and $T_{sink}$

Table 3 shows the industrial groups/unit operations analyzed via the pinch methodology and evaluated for the potential economic and technical impacts.

**Table 3. Industrial groups and unit operation analyzed**

| Industrial group | Unit operation | Heat source / sink temperature (°C) | Process heat demand |
|---|---|---|---|
| Paper | Pulp Mill – Digestor | 104/130 (economic)<br>53/127 (technical) | 0.2–0.5 MMBtus/ton pulp |
| | Pulp Mill – Multi-Effect Evaporator | 58/78 (economic)<br>63/102 (technical) | 0.3–1.3 MMBtus/ton pulp |
| | Non-Integrated Paper Mill – Pulper | 36/70 | 0.06–0.07 MMBtus/ton paper |
| Food | Wet Corn Milling – Steepwater | 57/90 (economic)<br>51/120 (technical) | 0.06–0.07 MMBtus/ton corn processed |
| | Wet Corn Milling – High fructose corn syrup starch conversion | 59/91 (economic)<br>53/97 (technical) | 0.02–0.17 MMBtus/ton corn processed |
| | Potato processing – Hot air dryer | 46/70 (economic)<br>41/110 (technical) | 0.4–1.0 MMBtus/ton potatoes processed |

| Industrial group | Unit operation | Heat source / sink temperature (°C) | Process heat demand |
|---|---|---|---|
| Chemicals | Ethyl Alcohol or Ethanol Fuel, dry mill | 78/100 | 4.5 MMBtus/ton ethanol produced, dry mill |
| | Ethylene (above ambient) – Debutanizer reboiler | 78/101 | 0.1 MMBtus/ton ethylene produced |
| | Ethylene (above ambient) – Process water stripper reboiler | 77/109 | 0.02 MMBtus/ton ethylene produced |

## ECONOMIC AND TECHNICAL POTENTIAL: SCENARIOS

The pinch analysis methodology provided the heat source, sink size (MMBtus/ton product), and temperature level (°C) for the economic analyses, assuming the IHP replaces the process heat supplied by an already installed, conventional process heating system (e.g., boiler steam or fired process heater), as shown in figure 4 (i.e., a retrofit IHP situation, not requiring new boiler or fired heater capital investment). To assess the potential energy savings we assessed both the "economic" and "technical" IHP potential. Figure 5 illustrates these two scenarios.

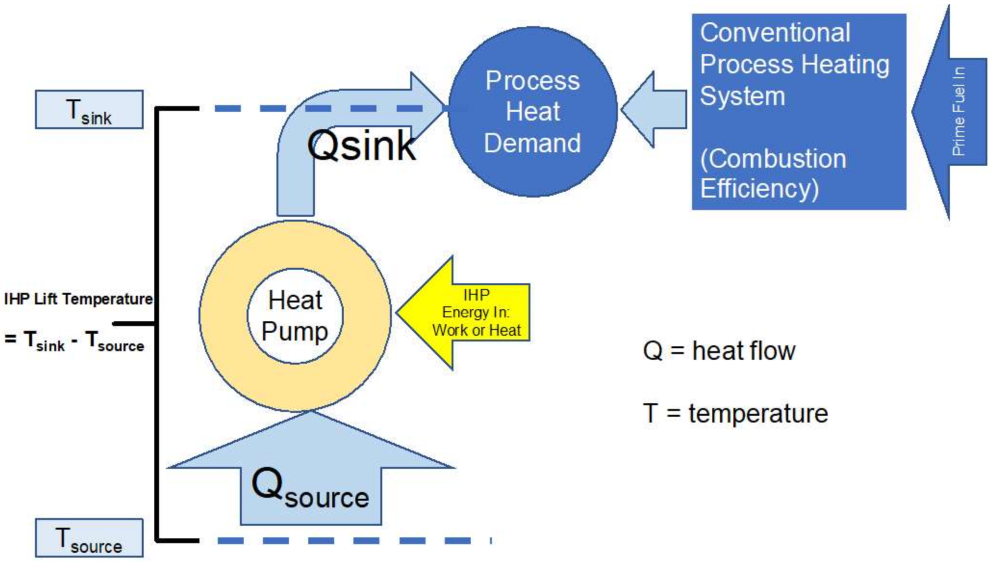

**Figure 4. Generic diagram of industrial heat pump alternatively supplying process heat**

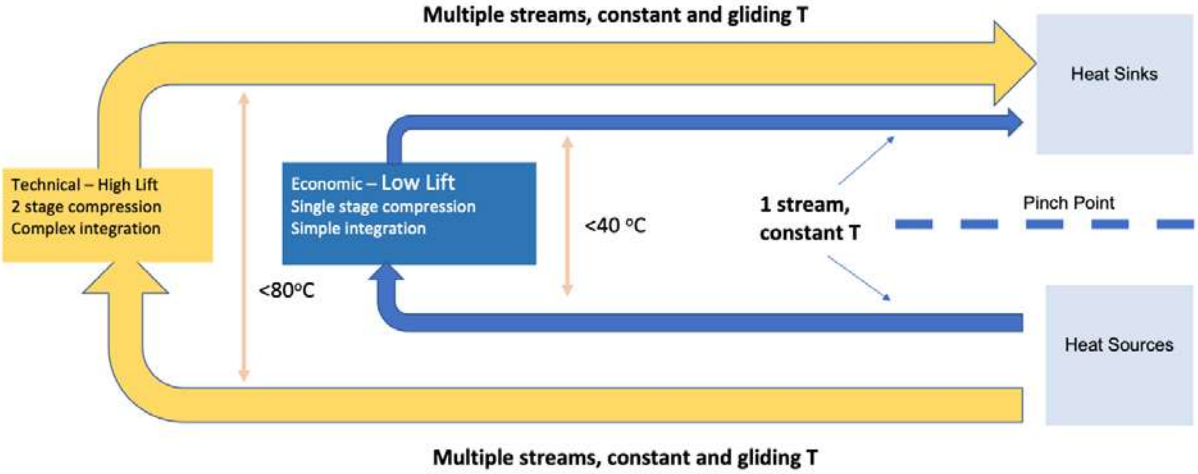

Figure 5. Economic and technical IHP potential energy savings

The economic potential case is simple when using one hot and one cold stream for the heat source and sink, respectively. Also, one constant condensing or evaporating (latent heat) stream was preferred as a heat source and/or sink to keep it to a simple configuration. The simplest cases were when both hot and cold streams were at a constant temperature, but that was not commonly found in all the unit operations. Finally, the IHP lift was limited to less than ~40 K, which is within the capability of a single-staged compression IHP.

Conversely, the technical potential case is much more aggressive in tapping into multiple heat sources and sinks at varying temperatures. Multiple IHPs were possible in this case. We did not limit the hot and cold streams to constant temperature, as they could offer a gliding temperature heat recovery or heat supply situation. The gliding temperature is when the heat source temperature will be reduced to capture the sensible heat and/or the heat sink temperature will be raised by the heat pump. The IHP lift temperature is higher and limited to less than 80°C for this case. Potential technical cases could require extensive engineering process redesign and heat integration changes to capture the estimated energy savings opportunity. Also, the compression heat pump in this case would require two stages of compression.

Note that the energy savings estimates are at two levels, economic and technical. Later in the report when we refer to the technical energy savings potential we mean the cumulative energy savings from both the economic and technical pinch analysis and the IHP energy savings of each level.

In both cases, we adjusted the capital costs of the IHP equipment and the installation costs assumed (more expensive for technical versus economic), see Appendix B, table B1; however, in summary MVR heat pump costs ranged from $250/kW to $500/kW, TVR costs were $150/kW, and the heat activated heat pump costs ranged from $1,000/kW to $1,875/kW. The IHP lift temperature will influence the amount of energy required to run the IHP.

Using the economic or technical cases, six different IHP types were evaluated for their cost effectiveness (simple payback) for the nine unit operations. In some unit operations, a heat pump type was ruled out due to mechanical limitations (e.g., TVR with heat pump lift greater than 20°C). The six selected represent those that are most likely to be installed currently. Figure 6 and table 4 conceptually introduce the six IHP types and show how they are driven with mechanical shaft power, prime heat, or waste heat. Note that $Q_{prime}$ is the thermal energy provided to the heat pump at a temperature higher than the heat sink and $Q_{ambient}$ is the heat rejected from the heat pump at the source temperature to the ambient temperature.

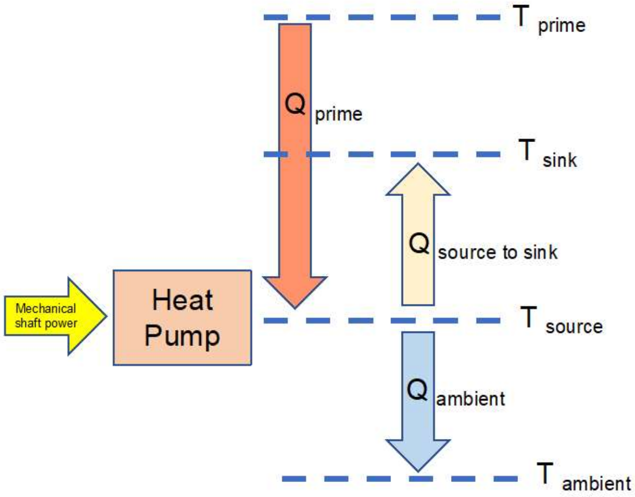

**Figure 6. Illustration of how the IHP types are driven, where Q = heat moved between the source and sink**

**Table 4. Characterization of six IHP types per figure 9**

| IHP type | Mechanical shaft power energy | Heat exchanger locations | $Q_{prime}$* | $Q_{ambient}$* | Technology readiness level (TRL) |
|---|---|---|---|---|---|
| Mechanical vapor compression, closed cycle (MVC) | Large | Sink and source | -- | -- | 9 |
| Mechanical vapor recompression, semi-open cycle (MVR Semi) | Large | Sink or source | -- | -- | 9 |
| Mechanical vapor recompression, open cycle (MVR Open) | Large | -- | -- | -- | 9 |

| IHP type | Mechanical shaft power energy | Heat exchanger locations | $Q_{prime*}$ | $Q_{ambient*}$ | Technology readiness level (TRL) |
|---|---|---|---|---|---|
| Thermal vapor recompression, open cycle (TVR Open) | -- | -- | Yes | -- | 9 |
| Heat activated heat pump, Type 1 (HA Type 1) | Small | Sink and source | Yes | -- | 4–7 |
| Heat activated heat pump, Type 2 (HA Type 2) | Small | Sink and source | -- | Yes | 4–7 |

### VALIDATION INTERVIEWS

The pinch studies provided an excellent starting point for an initial understanding of where an IHP could be optimally placed in the process, temperatures for the source and sink, lift, and the estimation of process-heat savings. However, as this information was based on process heating and cooling data with limited details of the unit operation type and dates (we were not able to clarify actual process details with the original source), the team sought to validate key assumptions, aspects of practical application, and barriers to adoption with industry experts. Working with industry associations and our networks, we identified subject matter experts who could provide input on the process flow as well as the process heat usage in that industrial group. The key findings from these discussions were incorporated into the analysis to select unit operations that could be more practically modified for heat pump installation. For example, the conversations directed us to certain waste heat sources in ethylene and wet corn milling that were more self-contained (e.g., simpler analysis).

### PARAMETERS AND RESULTS

Parameters, pinch analysis summaries, and results for the full range of IHPs examined across all applications/unit operations can be found in the Annex, sections 3–5. A listing of the carbon intensity emission factors used for natural gas and electricity can be found in Appendix C.

## Potential Applications of IHP in Example Industries

The potential for IHP adoption in the nine unit operations in selected industrial segments was examined to identify the most efficient, cost-effective, and impactful geographic location for IHPs. We examined IHP application in food manufacturing, using potato processing as an example since it is a simple process and uses a drying process (a common unit operation in industry). For additional unit operations, results are provided below, and additional details can be found in the appendices.

## FOOD

The food processing industrial group (NAICS code 311) is among the top five energy-consuming industries in the United States, and ranks fifth in energy use for process heating, using 532 TBtus/year (non-electric, EIA 2021a). The food industry is responsible for just over 3% of the nation's $CO_2$ emissions with 49 MMT $CO_2$ (EIA 2021a). Fluid heating, boiling, drying, and other preparation steps are among the top energy users. This industry is well distributed across the United States, with over 36,000 manufacturing plants owned by over 31,000 companies (USDA 2020), and 22 large facilities producing potatoes. There are also a multitude of product subsegments, including meats, beverages, dairy, grains, fruits and vegetables, animal foods, and bakery products. Several food products have similar processing steps where IHPs could be used to supply process heat, including pasteurization, blanching, sterilization, drying, and evaporation (New Zealand EECA 2019).

As a simple example for screening applicability, we chose the potato hot air drying process. In 2020, 279 million cwt (hundred weight or 112 lbs., equal to 15,668 thousand tons) of potatoes were processed (USDA 2021)[4]; the three top producing states were Idaho (32%), Washington (18%), and Wisconsin (7%). The estimate of total process heat utilized across the industry for processing of potatoes is 36.7 TBtus/year (50% of the process heat for fruit and vegetables, EIA 2021a). A portion of the potato process heat is for hot air drying. A summary of the analysis and results for the potato processing can be found in Annex, sections 3 and 5.

Figure 7 shows the generic potato drying process with the IHP applied. The heat pump's heat source is moist, hot air exiting the dryer and the heat sink is the inlet air. The heat pump preheats the dryer inlet air to reduce the steam consumption, and thus reduce the natural gas use for the boiler. In this example, the pinch analysis in the economic potential case found the heat pump lift temperature to be 34 K for a closed cycle MVC IHP.

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[4] Hundred weight (cwt) is referenced here as it is the unit of mass equal to 100 pounds used in the field. The translation to more common units is given in the parentheses.

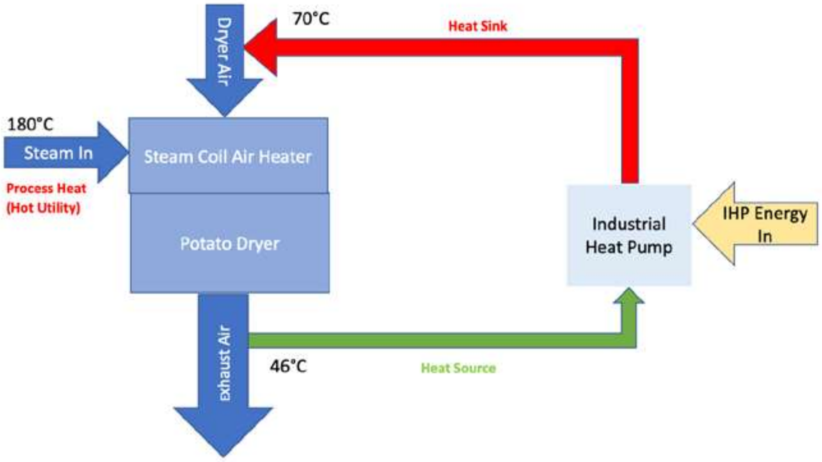


**Figure 7. Simple flow sheet for potato drying IHP application**

For practical reasons, the closed cycle MVC IHP designs would be the only IHP type considered for this type of food processing application, that is, to isolate the heat pump working fluid from the drying oven's inlet air stream. However, to illustrate comparative economics we show the results for all six IHP types. Analyses for the various heat pump types in figure 8 are for a typical potato processing facility (assuming all potato dryers have IHPs) under the economic potential case.

The results show that all the compression type IHPs (MVC, MVR Semi, MVR Open) save significant natural gas, about 11.4%. This is the case because the moist, hot air is a significant heat source relative to the preheated inlet air (heat sink). There are minor increases in electricity usage for the compression IHP types because the lift temperatures are modest at 24–34 K.

The TVR-Open Cycle results are shown for completeness even though TVRs require low lift temperature (less than 20 K) to operate. The immediate and greatest energy savings opportunity in the potato drying application is capturing the waste heat from the exhaust air of the dryer and using it to heat up the inlet air, thereby offsetting the steam demand (process heat). The TVR could be a fit here provided the temperature lift is within the thermodynamic and design limitations and there is a way to configure it with steam. However, in the potato drying unit operation that was considered in this report, even in the economic potential case, the temperature lift was found to be 24 K (the difference between the dryer air and the exhaust air temperatures). If this application used a steam TVR, it would further increase the temperature lift to probably 34 K, further limiting the TVR application. Hence, TVRs are not included in either of the economic or technical potential cases for potato drying IHP applications in table 5.

The HA Type 1 IHP's natural gas savings are modest (~3%) because it requires steam to operate and the heat pump's savings in preheating the dryer's inlet air are offset by the HA Type 1 IHP steam driver energy requirements. The waste heat driving force for the HA Type 2

IHP (dryer moist hot air temperature minus ambient temperature) is not ideal for waste-heat-driven heat pumps and thus is not applicable to the potato drying process.

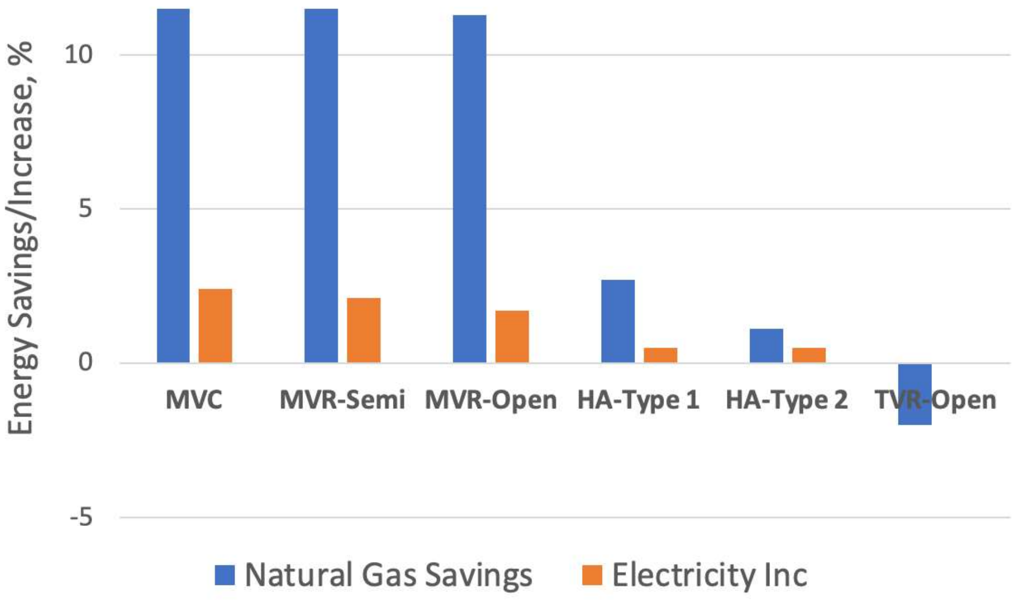


**Figure 8. Energy savings for the potato drying IHP types per facility, economic case**

An analysis of the $CO_2e$ emissions reductions is shown in figure 9 for the economic and technical potential cases for all potato drying facilities (22 facilities estimated). The IHP lift temperature makes a significant difference as the $CO_2$ savings for each IHP is influenced by the heat pump electricity requirements relative to the natural gas savings. We assumed carbon emission factors for natural gas and electricity based on current U.S. national grid averages: 0.005 metric tons $CO_2e$ per therm for natural gas and 0.0004 per metric tons $CO_2e$ per kWh for electricity in 2020, decreasing to 0.00025 and 0.0001 in 2035 and 2050, respectively (see Appendix C). The current U.S. electricity grid still has a fairly high carbon emission factor, but as the grid becomes cleaner the technical potential case will show even higher $CO_2$ reductions.

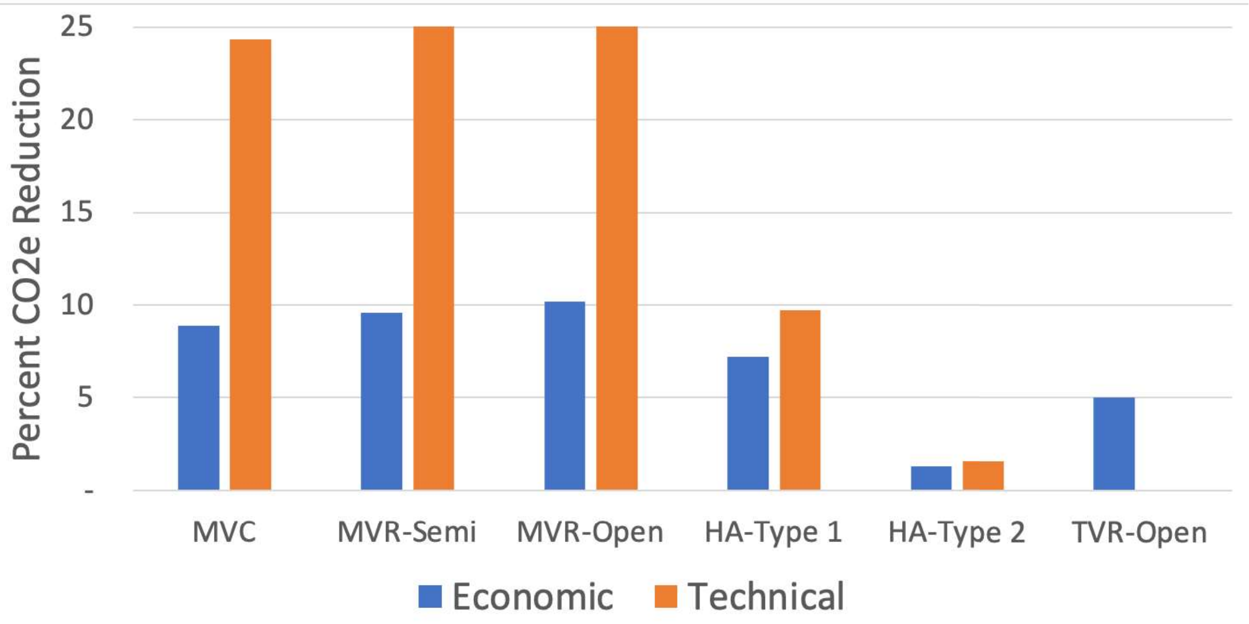


**Figure 9. $CO_2e$ reductions, (%) for economic and technical potential case, per potato drying facility**

Table 5 shows the relationship of natural gas savings, source energy savings, COP (see note below), and $CO_{2e}$ reductions for the economic and technical potential cases.

**Table 5. Summary of parameters for the potato drying economic and technical potential cases**

| | MVC | MVR Semi | MVR Open | HA Type 1 | HA Type 2 |
|---|---|---|---|---|---|
| IHP lift temp (economic), °C | 34 | 29 | 24 | 34 | 34 |
| IHP lift temp (technical), °C | 79 | 74 | 69 | 79 | 79 |
| Natural gas savings (economic) | 11.5 | 11.5 | 11.3 | 2.7 | 1.1 |
| Natural gas savings (technical), %* | 28.9 | 28.5 | 27.9 | –17.0 | 0.2 |
| Source energy savings (economic), %* | 5.8 | 6.6 | 7.3 | 1.6 | 1.0 |
| Source energy savings (technical), %* | 7.8 | 8.4 | 9.2 | –20.2 | 0.2 |
| COP (economic) | 5.1 | 5.9 | 7.1 | 2.4 | 0.1 |

| | MVC | MVR Semi | MVR Open | HA Type 1 | HA Type 2 |
|---|---|---|---|---|---|
| COP (technical) | 2.5 | 2.6 | 2.8 | 1.2 | 0 |
| $CO_2e$ reductions (economic), MMT/year | 0.13 | 0.14 | 0.15 | 0.11 | 0.02 |
| $CO_2e$ reductions (economic), % | 8.9 | 9.6 | 10.2 | 7.2 | 1.3 |
| $CO_2e$ reductions (technical), MMT/year | 0.23 | 0.24 | 0.25 | 0.04 | 0.01 |
| $CO_2e$ reductions (technical), % | 15.5 | 16.0 | 16.6 | 2.5 | 0.3 |

*** The percentage savings are relative to usage of natural gas or energy per facility for the potato drying unit operation before application of the IHP**

Note:

Source energy represents the total amount of raw fuel that is required for an end use application. It incorporates all generation, transmission, delivery, and production losses.

COP, coefficient of performance, is defined and described in Appendix A (IHP Types) in more detail, but very simply it is:

$COP = Q_{sink} / E_{driver}$

$Q_{sink}$ = amount of heat supplied by the heat pump to the heat sink

$E_{driver}$ = amount of energy input to drive the heat pump; can be electricity, prime or waste heat, or a combination thereof.

While the technical potential case always saves more natural gas than the economic potential case, it does not necessarily reduce $CO_{2e}$ emissions proportionately if the electricity demand goes up due to the higher IHP lift temperature (lowered COP). The compression-type heat pumps show an increase from the economic to technical potential cases since their COPs are still favorable (> 2.5) and they have good overall IHP energy savings, whereas the heat activated Type 1 COP decreases to as low as 1.2 at the higher lift temperature assumed for this study (e.g., 80°K versus < 40°K) and thus there is minimal additional $CO_{2e}$ emissions reduction for the HA Types 1 and 2 going from the economic to the technical potential case.

Simple payback was derived from the estimated energy cost savings and total installed capital cost (see Appendix B). However, capital costs ranged from $250 to $800 per kW for heat delivered for the vapor compression IHP types (MVC, MVR Semi, and MVR Open), $150 per kW for the TVR, and from $1,000 to $1,875 per kW for the HA Types 1 and 2 (table 10).

As an example of one IHP type, a plot of the simple payback for the economic potential case (figure 10) for the MVC IHP shows that at a low natural gas price there is a significant spread in the payback, but as the natural gas price increases, the spread narrows considerably. This is the result of the overall process heat operating savings being composed of the natural gas savings plus the savings attributed to decreased need for pollution control and cooling tower water chemicals—and this cost is more than three times the electricity costs for running the heat pump. That is, with high natural gas costs, the influence of other factors associated with burning natural gas and producing steam has a stronger influence on the payback than the relatively small electricity costs for running the heat pump. When the natural gas price is high, the savings afforded by IHPs brings the payback to well under two years. However, at lower natural gas prices (e.g., $3 per MMBtus or $2.84 per gigajoule (GJ)), the electricity price will have a strong influence on the payback.

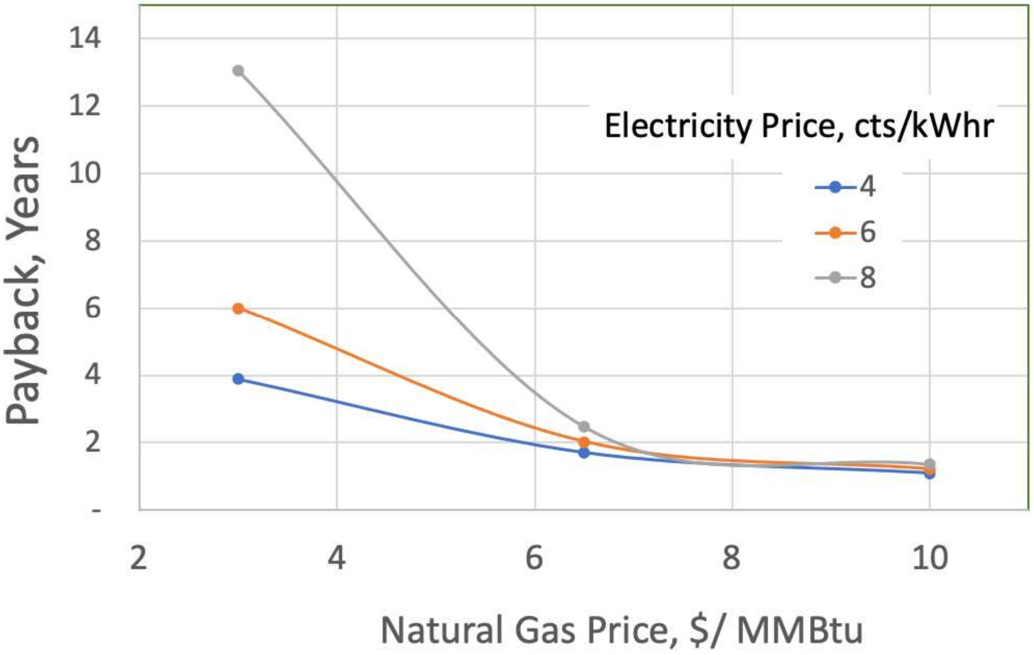


**Figure 10. Simple payback for the potato drying application at various electricity prices for the MVC IHP with a capital cost of $250 per kW**

The general trends of greater payback sensitivity to the electricity price when the natural gas price is low and relative insensitivity when the natural gas price is high are observed across the IHP types, as shown in figure 11. The paybacks for the compression type IHPs demonstrate payback from 1–8 years across the range of natural gas and electricity prices assumed in the analysis. However, the HA Type 1 has higher paybacks (e.g., >10 years) and requires higher natural gas prices to provide reasonable payback (e.g., less than 6 years). It should be noted that the capital costs assumed for the heat activated heat pumps were from

$1,000 to $1,875 per kW [this work]. However, because heat activated heat pump designs are generally at TRL 7 or lower we can anticipate that with additional RD&D these costs could decrease significantly over time (Scheihing 2021). Likewise, while not plotted on figure 11, note that the paybacks on investment for the technical potential case were under four years for the vapor compression heat pumps when natural gas prices were over $6.5 per MMBtus.

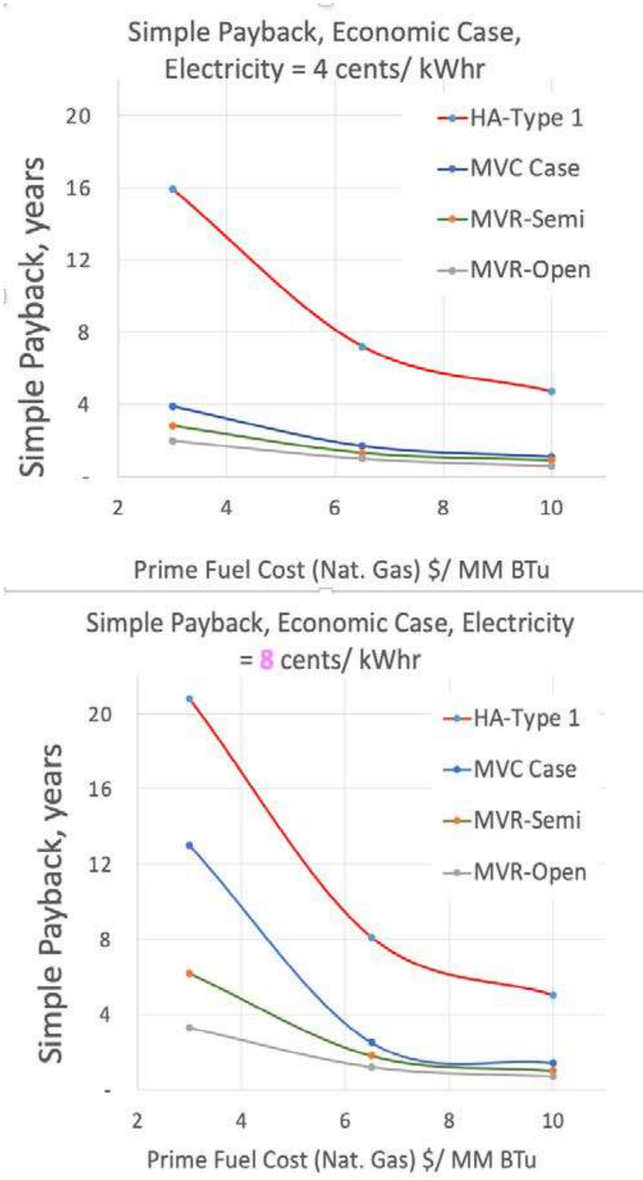
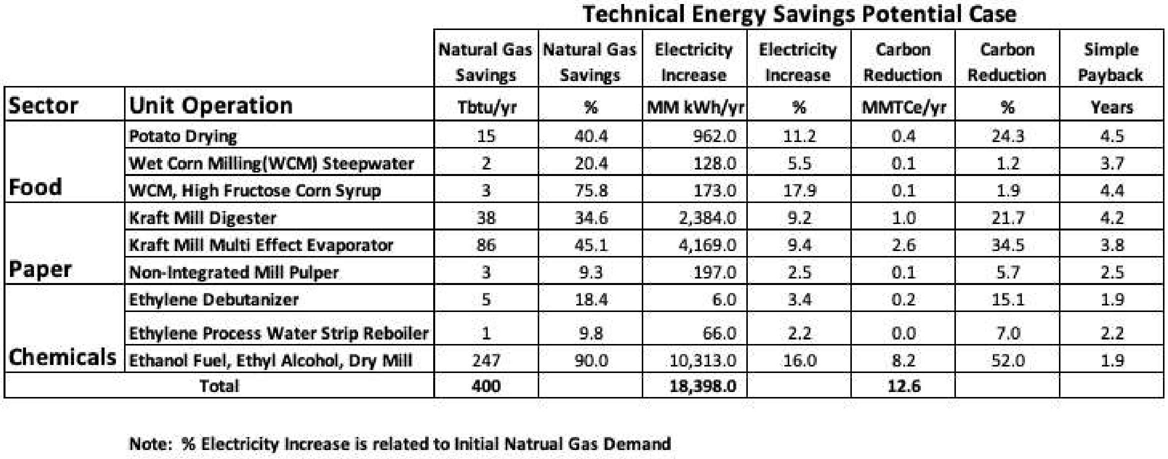


**Figure 11. Payback versus natural gas cost for four IHP types at 4 (above) and 8 cents/kWh (below) electricity cost for the potato drying application, assuming capital costs from $250–1,000 per kW for a single facility**

## IHP SUMMARY ACROSS ALL INDUSTRIAL GROUPS AND UNIT OPERATIONS

Now we shift from describing the results for just the potato process unit operation to the results for IHPs across all industrial groups and unit operations studied (nine unit operations). Table 6 shows the results for all facilities in the nine unit operations for the MVC IHP case, with natural gas prices of $6.50/MMBtus and an electricity price of 6 cents/kWh. This could be considered an upper estimate at 100% market penetration. While this may be a high estimate it should be noted that dual heating and cooling IHP opportunities were not yet included and the benefits of downsizing the process heat load from current steam systems (e.g., oversized boilers, steam losses) were not accounted for.

**Table 6. Summary of results across all unit operations for the economic and technical potential case and MVC IHP**



**Technical Energy Savings Potential Case**

| Sector | Unit Operation | Natural Gas Savings Tbtu/yr | Natural Gas Savings % | Electricity Increase MM kWh/yr | Electricity Increase % | Carbon Reduction MMTCe/yr | Carbon Reduction % | Simple Payback Years |
|---|---|---|---|---|---|---|---|---|
| Food | Potato Drying | 15 | 40.4 | 962.0 | 11.2 | 0.4 | 24.3 | 4.5 |
| | Wet Corn Milling(WCM) Steepwater | 2 | 20.4 | 128.0 | 5.5 | 0.1 | 1.2 | 3.7 |
| | WCM, High Fructose Corn Syrup | 3 | 75.8 | 173.0 | 17.9 | 0.1 | 1.9 | 4.4 |
| Paper | Kraft Mill Digester | 38 | 34.6 | 2,384.0 | 9.2 | 1.0 | 21.7 | 4.2 |
| | Kraft Mill Multi Effect Evaporator | 86 | 45.1 | 4,169.0 | 9.4 | 2.6 | 34.5 | 3.8 |
| | Non-Integrated Mill Pulper | 3 | 9.3 | 197.0 | 2.5 | 0.1 | 5.7 | 2.5 |
| Chemicals | Ethylene Debutanizer | 5 | 18.4 | 6.0 | 3.4 | 0.2 | 15.1 | 1.9 |
| | Ethylene Process Water Strip Reboiler | 1 | 9.8 | 66.0 | 2.2 | 0.0 | 7.0 | 2.2 |
| | Ethanol Fuel, Ethyl Alcohol, Dry Mill | 247 | 90.0 | 10,313.0 | 16.0 | 8.2 | 52.0 | 1.9 |
| Total | | **400** | | **18,398.0** | | **12.6** | | |

Note: % Electricity Increase is related to Initial Natrual Gas Demand

The total source energy savings across all industrial groups and unit operations are shown in figure 12. This plot shows that the total source energy savings is significantly higher for the technical potential cases than expected, given the assumption of more extensive application of IHPs. Although lower energy savings are shown for the HA types, it is expected that greater use of waste heat in the future will be enabled by heat activated heat pumps since they can lift heat over higher temperatures without penalty of high electricity operational costs. Heat activated systems could also prove to be more flexible in operating over wide turndown ratios within processes and thus increase the energy savings potential as they are further developed and deployed. The MVR Semi and MVR Open IHPs each show higher energy savings improvement over the MVC heat pump, reflecting the fact that not requiring one (semi-open) or two (open) heat exchangers to capture waste heat vapors yields higher heat pump COPs; for example, high pump lift temperatures are lower than for the MVC type. The elimination of heat exchange translates into overall source energy savings.

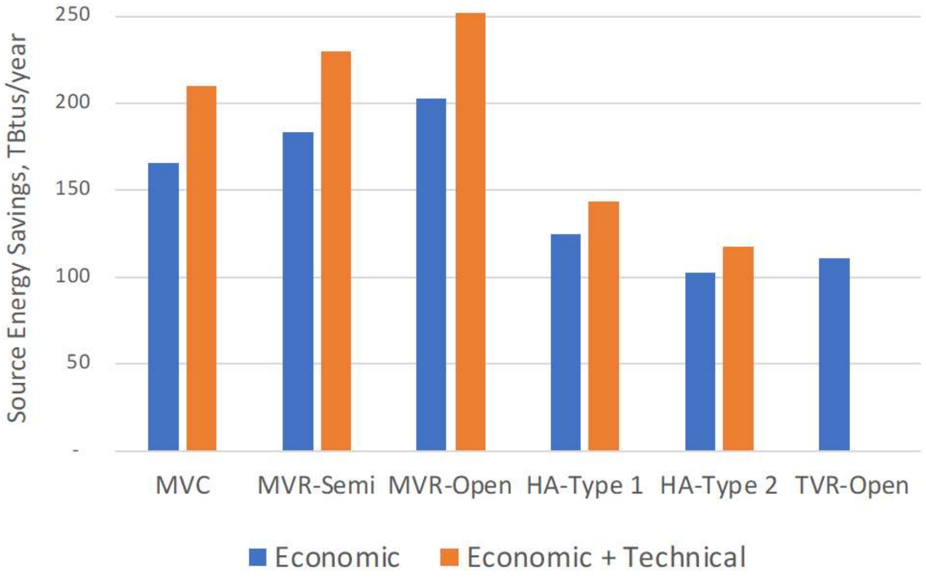


**Figure 12. Summary of source energy savings for all nine unit operations combined for the "economic" and "economic + technical"**

While the IHPs save natural gas, electricity is required to run the compressors for the MVC, MVR Semi, and MVR Open heat pumps. The heat activated heat pumps (HA Type 1 and HA Type 2) do require less electricity than the MVC, MVR Semi, and MVR Open heat pumps, but their COPs are lower and thus the thermal energy (natural gas) is lower. Figure 13 shows the magnitude of the energy changes for natural gas and electricity usage for all nine industrial groups analyzed. Here the increased electric load is shown to the right of the *y*-axis, and the natural gas decrease is shown to the left. Looking at the MVC, MVR Semi, and MVR Open types, the natural gas savings are similar, but the electricity decreases in this order. For the MVC (closed cycle), electricity is used to compress refrigerant vapors, and there are heat exchangers at both the source and sink so the heat pump lift will be higher, requiring additional electrical energy. The MVR Semi eliminates one heat exchanger and the MVR Open eliminates two heat exchangers, so the lift is lower resulting in somewhat lower electricity needs. The HA types require much lower amounts of electricity since they pump liquids and do not compress vapors, but as mentioned, their lower heating COP, compared to vapor compression heat pumps, yields a lower net energy savings.

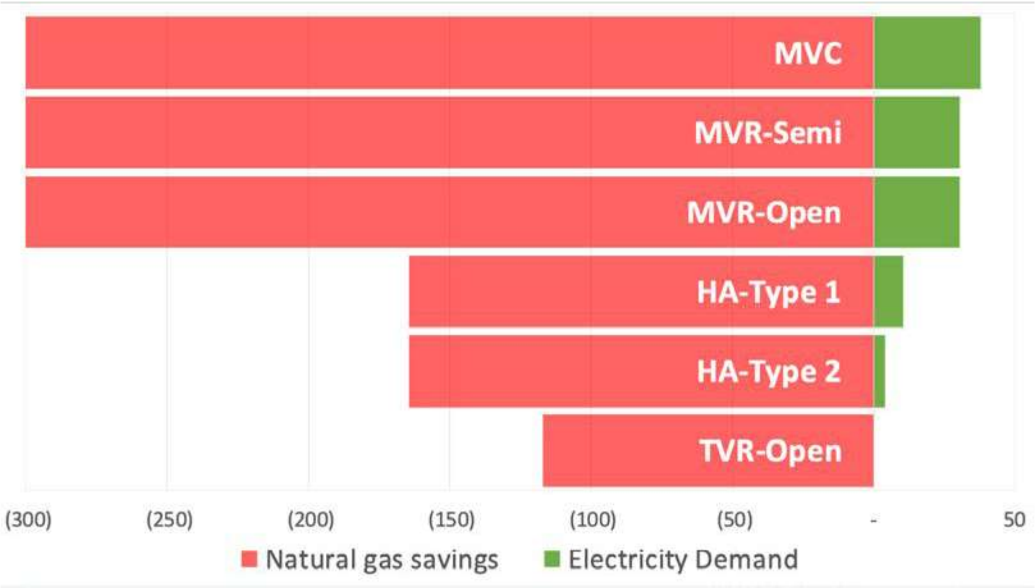


**Figure 13. Energy changes across all nine unit operations, economic case, TBtus/year**

Figure 14 shows the changes from a carbon perspective, where it is evident that the increase in carbon emissions from electricity (right, green) is significantly less than the reduction in carbon emissions from the decrease in natural gas use (left). Hence, there is an overall net decrease in $CO_2e$ emissions. As the grid incorporates more low-carbon energy and the emissions factors decrease, the carbon emissions footprint for electricity will decrease, so the difference between the electricity and natural gas bars will become larger for the other types as well.

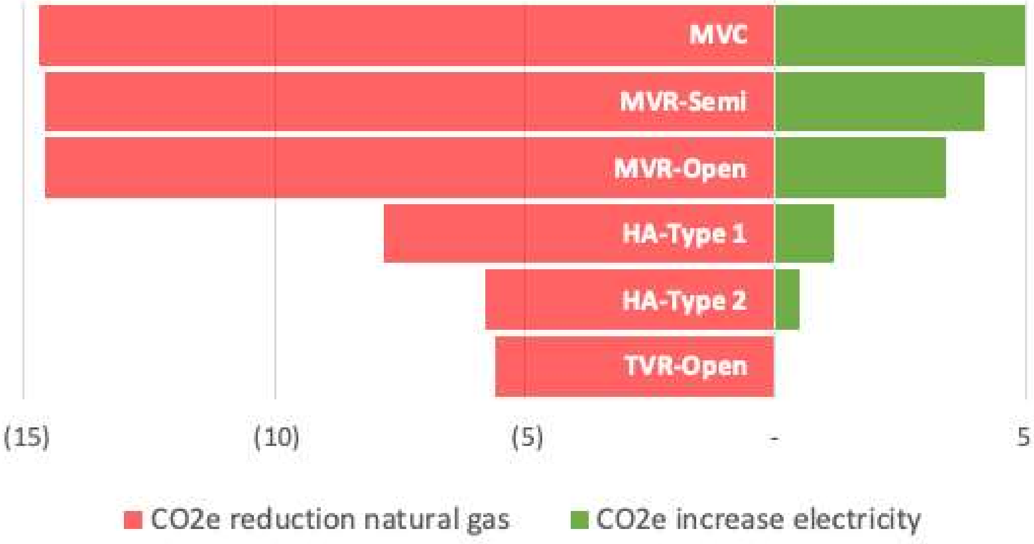


**Figure 14. Changes in $CO_2e$ emissions for the IHP types across all unit operations, economic case, in millions of metric tons $CO_2e$/year**

As the grid adds more low-carbon generation, the carbon emissions factors for the grid will decrease (see Appendix C), and the $CO_2$ reductions delivered by IHPs will increase (as the electricity to run the compressors will have a lower carbon intensity), as shown in figure 15. For simplicity, we assumed a static fuel mix and process heating demand to show that the impact of $CO_2$ reductions would grow as the electric grid becomes decarbonized. It is possible that the amount of waste heat demand could diminish over time due to structural changes in manufacturing, further process heat integration, and process technology innovations.

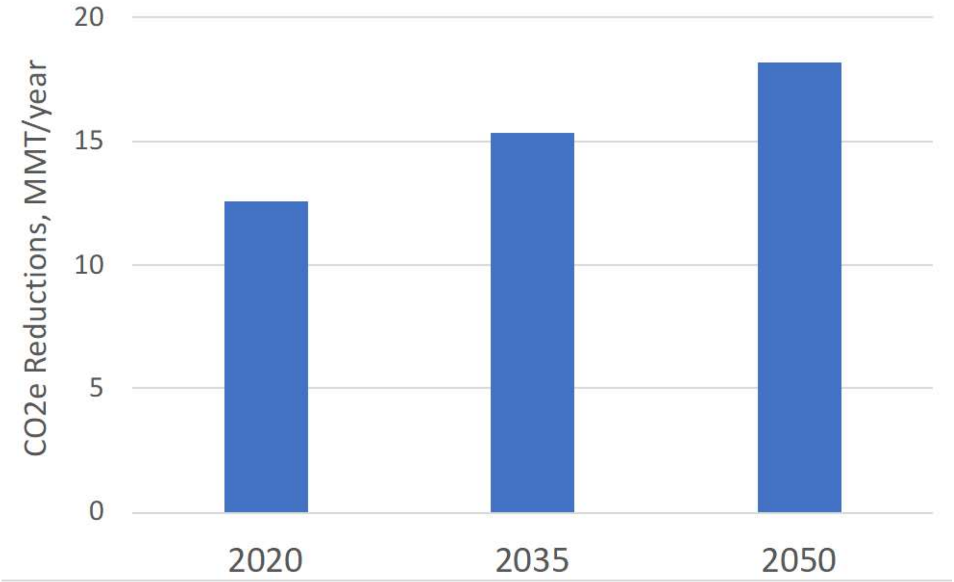


**Figure 15. $CO_2e$ reductions across all unit operations for economic + technical potential (paper pulper, ethyl alcohol, ethylene debutanizer, and ethylene process water stripper reboiler contributes at economic potential only; see text). Estimates for 2035 and 2050 use carbon emissions factors for electricity that are reduced due to more low-carbon generation.**

For 2020 the amount of $CO_2e$ reduction potential for the unit operations studied ranges from 9.7–12.6 MMT $CO_2e$ /year, which is equivalent to the emissions from 2.1–2.8 million cars/year or the emissions associated with generating power to serve 1.1–1.5 million homes for a year (EPA 2021). With lower emissions factors for grid-produced electricity expected by 2050, the reduction potential would be 13.4–18.2 MMT $CO_2e$/year.

Contributions for the paper pulper, ethylene (debutanizer and process water stripper reboiler), and ethyl alcohol/ethanol fuel operations added only their economic potential carbon reductions to the total across the nine unit operations; the technical potential case for these unit operations was not possible as the process heat data available were not of sufficient quality and reflective of current processes to provide a credible estimate. Also, a more sophisticated and higher-fidelity level of the pinch analysis tool would be needed to provide a plausible estimate. Further details for the chemicals unit operations are in Appendix F.

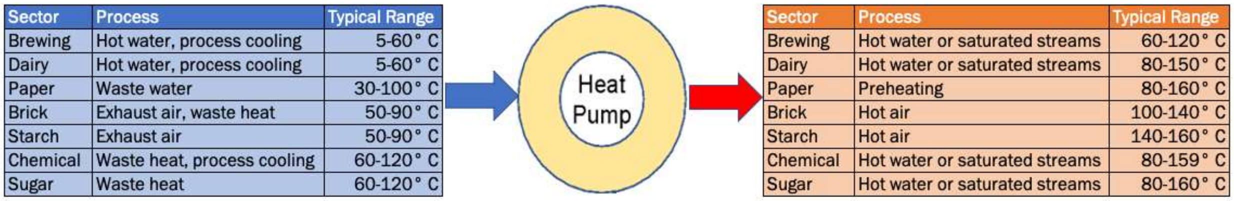
# The Technology Fit for Applications

The application of IHPs to upgrade process heat are one of several significant solutions to systematically optimize industrial processes in order to drive them closer to their practical minimum energy performance, and thus, to reduce energy consumption and carbon emissions. At a deeper applications level there are several insights for areas where IHPs could do particularly well in reducing energy and carbon emissions and aiding the transition to low-carbon electricity in industry. The application of IHPs to upgrade process heat can be considered as part of a holistic approach to reducing energy use and carbon emissions. It can be complimentary to a systems efficiency drive that addresses cross-cutting and process-specific opportunities. Studies on energy efficiency opportunities in specific industrial groups are part of that context, for example, studies in pulp and paper (Kramer, Masanet, and Worrell 2008). IHPs could have complementary benefits in the following areas, considering the insights of this work.

**Types and fit with applications.** The MVC and MVR IHPs would do well in IHP applications below 40 K lift, especially with condensing and evaporating streams for heat sources and sinks. This is because the electricity requirements increase substantially above 40 K lift temperature and the payback on investment becomes much greater than three years. TVRs work best with lift temperature less than 20°C and for steam only applications. The TVR's lower capital cost and lack of moving parts makes it attractive and durable. Further discussion on the applicability of TVRs can be found in Appendix D.

The HA Types 1 and 2 will be more competitive with the electric-driven vapor compression heat pumps for lift temperatures between 40 K and 80 K. While the heat activated heat pumps currently are estimated to have capital costs two to three times higher than vapor compression heat pumps, they show great potential, can lift heat efficiently up to 100°C, and should be more able to adjust to changing process conditions without performance degradation. As mentioned previously, because heat activated heat pump designs are generally less mature, we could expect further RD&D to significantly reduce these costs. Additional discussion on the heat activated IHPs can be found in Appendix E.

The food and beverage, chemicals, pulp and paper, and refining industrial groups could be early candidates for applications, as noted in figure 16. These industrial groups have relatively high levels of low-medium grade process heat (< 200°C, see figure 2), which would be suitable for current and emerging IHP use. Although heat integration and pinch analysis is common for world class chemicals facilities, additional optimization is of interest as the product mix, technology, and new drivers evolve (e.g., carbon emissions constraints). Also, it should be noted that the use of heat integration and pinch analysis is less prevalent for small- and medium-sized manufacturers and light industry (e.g., food and beverage, metal casting, and others). A compilation of current applications for IHPs finds a number of examples of IHPs already being used in these industrial groups around the globe.[5] COPs above 3 are common in these applications and multiple case studies are available (New Zealand EECA 2019).



| Sector | Process | Typical Range |
|---|---|---|
| Brewing | Hot water, process cooling | 5-60° C |
| Dairy | Hot water, process cooling | 5-60° C |
| Paper | Waste water | 30-100° C |
| Brick | Exhaust air, waste heat | 50-90° C |
| Starch | Exhaust air | 50-90° C |
| Chemical | Waste heat, process cooling | 60-120° C |
| Sugar | Waste heat | 60-120° C |

| Sector | Process | Typical Range |
|---|---|---|
| Brewing | Hot water or saturated streams | 60-120° C |
| Dairy | Hot water or saturated streams | 80-150° C |
| Paper | Preheating | 80-160° C |
| Brick | Hot air | 100-140° C |
| Starch | Hot air | 140-160° C |
| Chemical | Hot water or saturated streams | 80-159° C |
| Sugar | Hot water or saturated streams | 80-160° C |

**Figure 16. Illustration of potential IHP applications from lower (blue) to higher (orange) temperatures. Source: DryFiciency 2021 chart and data augmented in this work.**

**Regionality.** The payback estimates shown earlier for potato drying (figure 10, table 6) show that for the MVC and MVR IHPs with natural gas at $6.5/MMBtus and electricity at 4–8 cents/kWh, the paybacks range from two to four years, which will be worthy of discussion at industrial companies. This is a ratio of about 1.8–3.6 for electricity/natural gas price on an equivalent MMBtus basis. There are already a number of states where the ratio of electricity/natural gas is currently below that number, as shown in figure 17. In these states there could be early IHP adoption opportunities, especially in the food industry where the capital costs, integration, and complexity are relatively low. Locally the ratio will also vary as different providers can have different electricity prices, and large industrial companies may have negotiated rates lower than the state average. Volatility in energy prices may change the map shown in figure 17, based on 2020 data, so local updated information should be considered as policy approaches are developed.

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[5] J. Leak, Australian Alliance for Energy Productivity, pers. comm., October 2021.

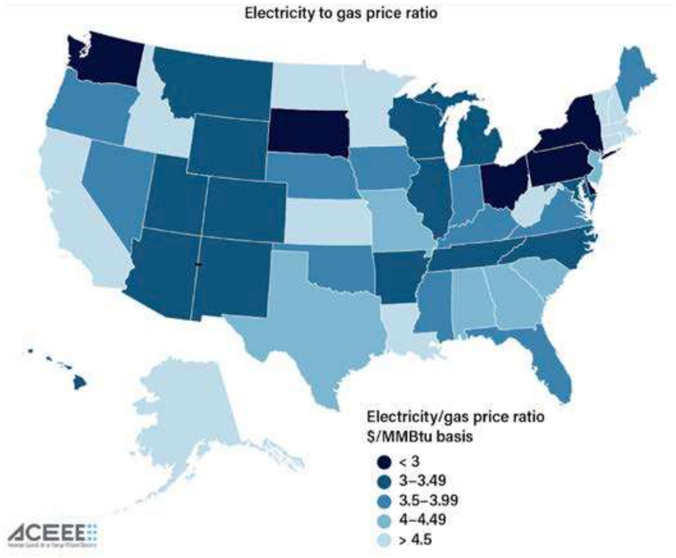


Figure 17. Illustration of electricity/gas price ratio by state

## ECONOMIC GAP

Figure 18 shows the influence of the electric/natural gas price ratio on payback for the paper digester example with the three mechanical vapor compression type IHPs. The payback results are influenced by having two heat exchangers (MVC, closed cycle), one heat exchanger (MVR, semi-open cycle), and no heat exchangers (MVR, open cycle). The use of heat exchange influences the heat pump lift temperature, heat pump COP, electricity consumption, and capital cost. The electricity/gas price ratio can lead to an economic gap that needs to be closed for IHPs, particularly in states where the ratio is high. For example, with the paper digester unit operation, when the electric/gas price ratio is greater than 4 and the natural gas price = $3/MMBtus, the simple payback will be more than two years for the MVR IHPs, except for MVR open cycle, as shown in figure 18.

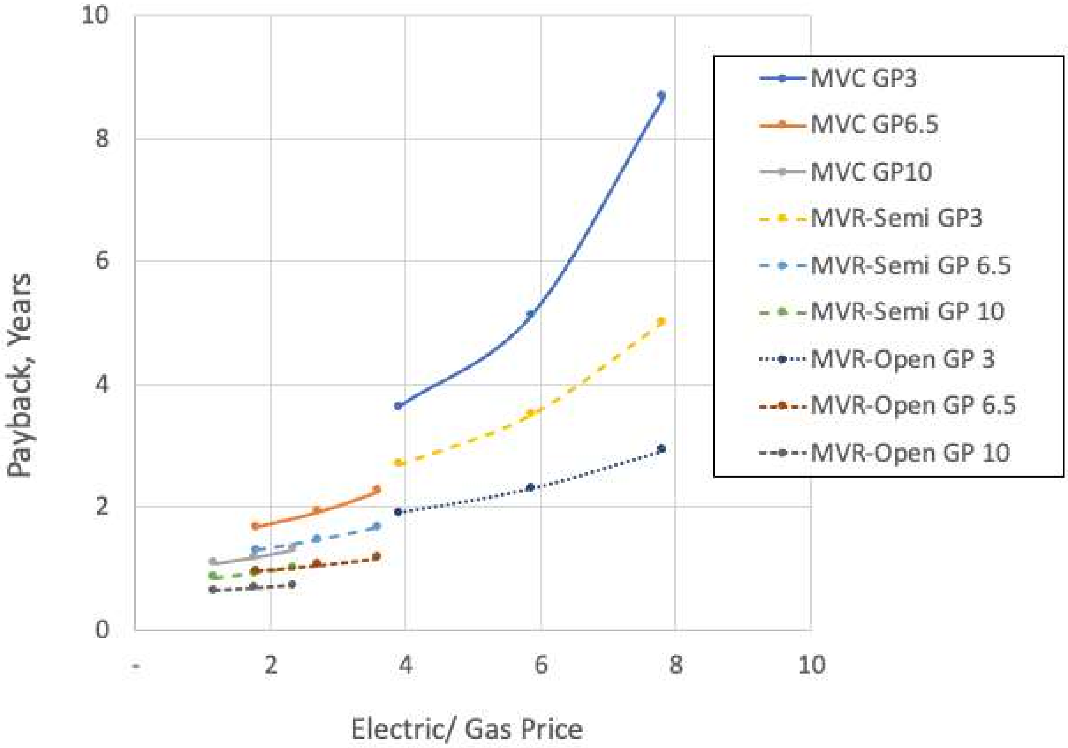


**Figure 18. Payback as a function of electric/gas price for the paper digester, economic case**

Examining this economic gap further when the natural gas price = $3/MMBtus shows that to reach the payback target of two years the capital for the IHP would have to be reduced 22% for the MVR, open and 40–67% for the MVC IHP, as shown in figure 19.

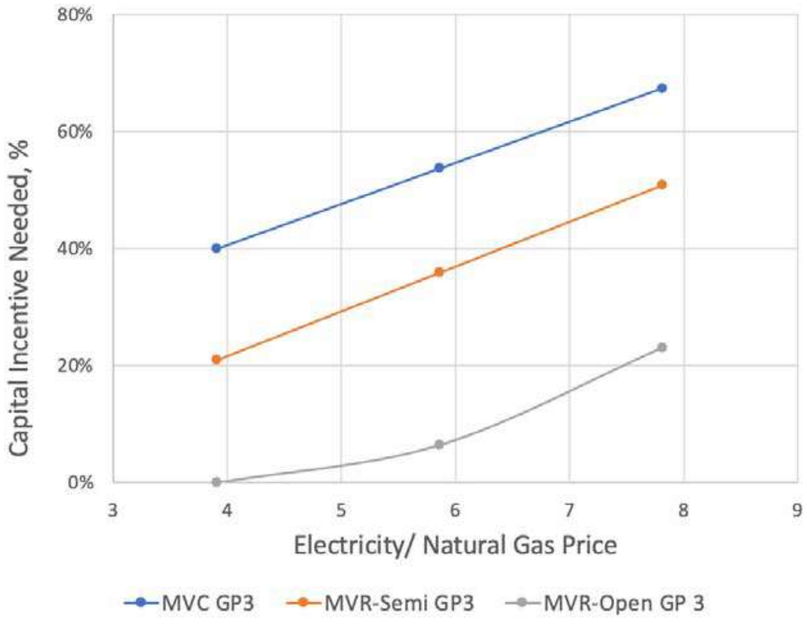


Figure 19. Capital adjustment needed to reach a two-year payback for the paper digester

## SCALE OF IMPACT

There can be multiple unit operations for each process considered in this work, so it can be challenging to understand the scale of impact. For example, the ethylene debutanizer and the process water stripper reboiler were examined for IHP potential, but these operations are a small portion of those in ethylene production, and only the unit operations above ambient were considered in this work (e.g., no analysis was performed in the cold section). In figure 20, a high-level perspective is given of the total industrial energy consumption with the three industrial groups examined in this report (left; chemicals, food, paper), and an expansion of those industrial groups' total energy use (right). The industrial groups where unit operations were analyzed are pulled out on the right (paperboard mills, pulp mills, fruit and vegetables, and ethyl alcohol).

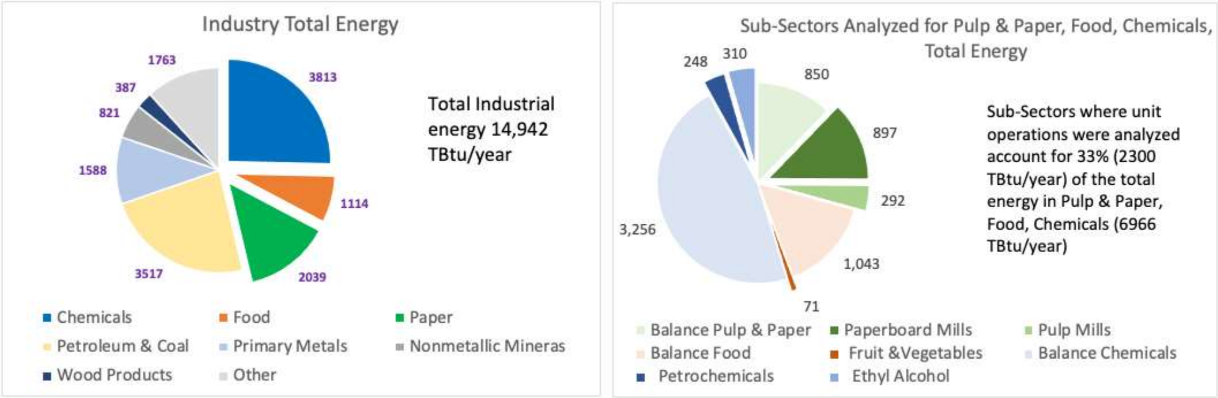


Figure 20. Energy use across all of industry (left; industrial groups examined in this work are in expanded slices), and proportion of in process heat energy for industrial groups examined in this work (right)

The potential for IHPs to save energy and reduce emissions in these industrial groups (separated in figure 20) is examined further for each industrial group below.

### IHP Impact in Food

In the food industrial group, three unit operations were analyzed (wet corn milling, corn steeping; wet corn milling, high fructose corn syrup; and potato drying) that account for approximately 10% of the industrial group's process heating demand, as shown in figure 21. For the MVC heat pump energy savings estimates, these three unit operations are projected to save between 11.3% (economic potential) and 39.6% (technical potential) of the process heating demand, if fully implemented in all facilities with these unit operations. Across all 78 facilities, IHPs could supply an estimated 535 MW of process heat through heat pumping. As noted earlier this would be considered a conservative, upper bound.

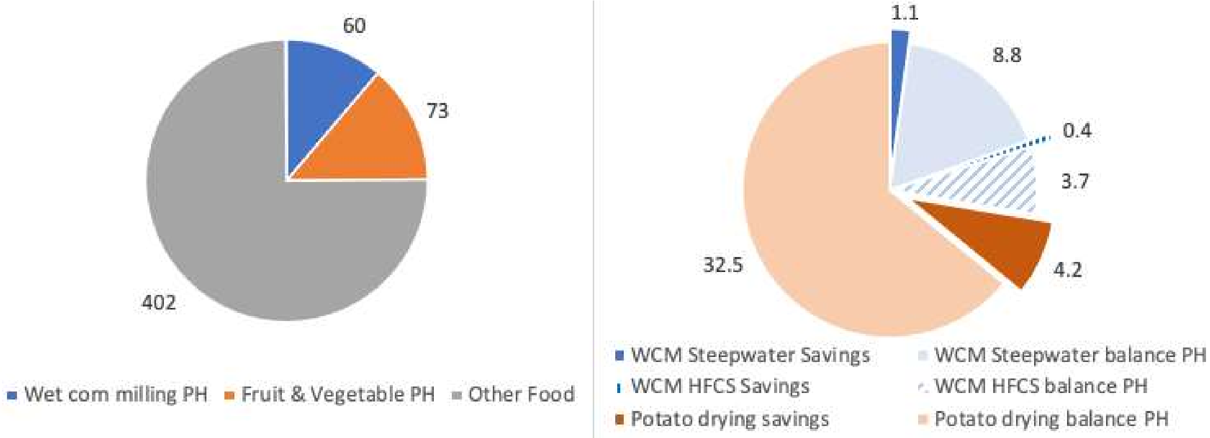


**Figure 21. Food industrial group process heat energy (PH) by industrial group (left), and unit operations analyzed within those groups (right) with the IHP process heat savings (slices pulled out) and PH balance for the three unit operations analyzed within the food industry. Units are in TBtus/year.**

Within these 78 facilities, under the technical scenario, natural gas savings are estimated at 20.0 TBtus/year with an IHP electricity requirement (increase) of 1,263 million kWh/year and 7.1 TBtus/year (4.8%) source energy savings, in aggregate. Carbon savings are estimated to be 0.5 MMTCe/year using the current U.S. average carbon intensity for electric power generation but could be 0.9 MMTCe/year by 2050 with the projected electric grid providing 75% lower carbon intensity.

Additional IHP savings are possible for the other 90% of the food industrial group's process heating demand, with the industrial group's widespread evaporation and drying unit operations. We estimated 400 TBtus/year of process heating energy demand could be targeted by IHP applications within the food industrial group (the remaining process heating demand was not analyzed). If IHP implementation resulted, conservatively, in energy savings of one-third of the technical potential percentage savings from IHPs of the three unit operations analyzed (about 5% savings), this would amount to an additional 19 TBtus/year of source energy savings, making the overall energy savings potential for the food industrial group 26 TBtus/year. Carbon savings are estimated at 1.8 MMTCe/year using current carbon intensity for U.S. power plants but could be 3.1 MMTCe/year by 2050.

### EXTRAPOLATED PAPER INDUSTRIAL GROUP IHP ENERGY-SAVING RESULTS

In the paper industrial group, three unit operations were analyzed (digester and multi-effect evaporator in Kraft paper mills, and the pulper in non-integrated paper mills) that account for approximately 43% of the industrial group's process heating demand. For the MVC heat pump energy savings estimates, these three unit operations are estimated to save between 10.3% (economic potential) and 41.3 % (technical potential) of the process heating demand, if fully implemented in all facilities with these unit operations. Across all the estimated 338 facilities, IHPs could save 127 TBtus/yr. natural gas through 338 facilities with an estimated cumulative 3,402 MW of heat pumping capacity (technical potential).

Within these 338 facilities, under the technical potential case, natural gas savings are estimated at 127 TBtus/year with an IHP electricity requirement (increase) of 6,750 million kWh/year and 58 TBtus/year (16.4%) source energy savings, in aggregate. Carbon savings are estimated to be 3.7 MMTCe/years using the current U.S. average carbon intensity of electric power generation but could be 5.7 MMTCe/year by 2050 with the projected electric grid providing 75% lower carbon intensity.

Additional IHP savings for the other 57% of the paper Industrial group's process heating demand are possible with the industrial group's widespread evaporation and drying unit operations. We estimated that 455 TBtus/year of process heating energy demand could be targeted by IHP application within the paper industrial group. If IHP implementation resulted, conservatively, in one-third of the technical potential percentage savings from IHPs of the three unit operations analyzed (about 6% savings), this would amount to an additional 25 TBtus/year source energy savings, making the overall energy savings potential for the paper industrial group 83 TBtus/year. Carbon savings are estimated at 5.2 MMTCe/year using current carbon intensity for U.S. electric power generation but could be 8.0 MMTCe/year by 2050.

### EXTRAPOLATED CHEMICALS INDUSTRIAL GROUP IHP ENERGY-SAVING RESULTS

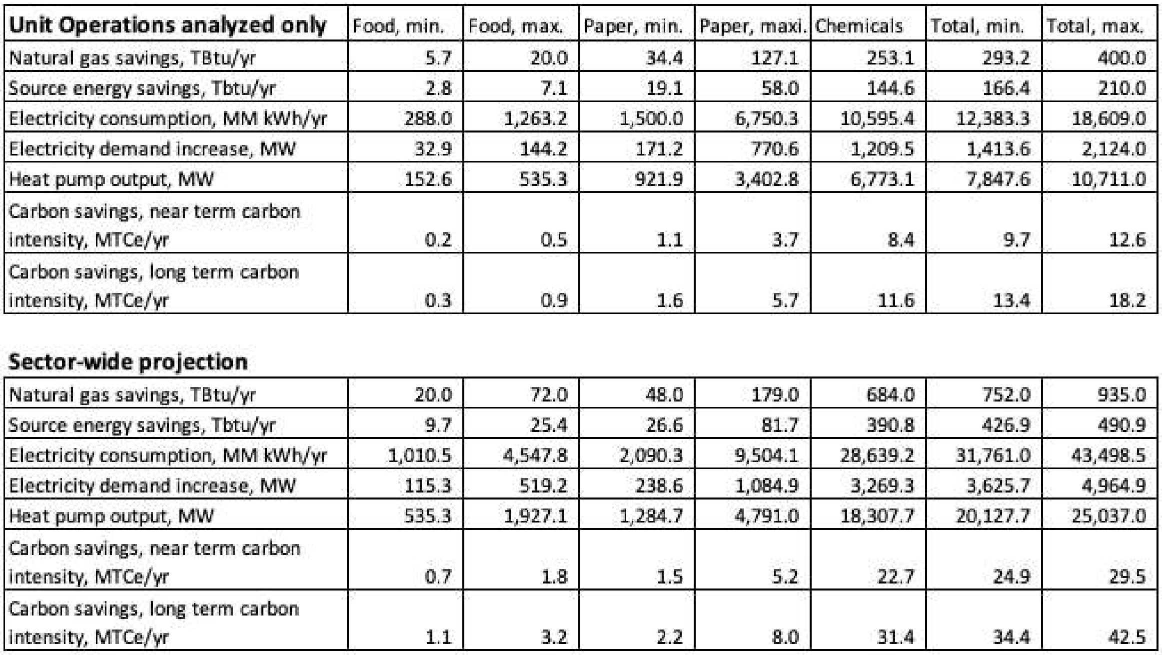
In the chemicals industrial group, three unit operations were analyzed (ethylene debutanizer, process water stripper reboiler, and ethanol dry mill distillation of ethanol-water mixture) that account for approximately 16.2% of the industrial group's process heating demand. Ethanol (fuel) makes up a large portion of that contribution. Although ethylene is also a large energy-consuming process, the two unit operations selected are just a small portion of the overall energy use. For the MVC heat pump energy savings estimates, these three unit operations are projected to save 80% of the process heating demand if fully implemented in all facilities with these unit operations; the heat pump applied to the ethanol distillation to remove water from ethanol saved 90% in process heat. Across all 256 facilities, IHPs could supply an estimated 6,773 MW of process heat through heat pumping.

Within these 256 facilities, under the technical potential case, natural gas savings are estimated at 253 TBtus/year with an IHP electricity requirement (increase) of 10,595 million kWh/year and 145 TBtus/year (26.7%) source energy savings, in aggregate. Carbon savings are estimated to be 8.4 MMTCe/year using the U.S. average carbon intensity of electric power generation but could be 11.6 MMTCe/year by 2050 with the projected electric grid providing 75% lower carbon intensity.

Additional IHP savings are possible for the other 84% of the chemicals industrial group's process heating demand, with the industrial group's widespread distillation, evaporation, and drying unit operations. We estimated 1,624 TBtus/year of process heating energy demand could be targeted by IHP application within the chemicals industrial group. If IHP implementation resulted conservatively in one-third of the technical potential percentage savings from IHPs of the three unit operations analyzed this would amount to an additional 273 TBtus/year of source energy savings, making the overall energy savings potential 418 TBtus/year (about 20% process heat savings). Carbon savings are estimated at 23.5 MMTCe/year using the current carbon intensity for U.S. electric power generation but could be 30.5 MMTCe/year by 2050.

Table 7 summarizes the results for the nine unit operations analyzed in the three industrial groups, as well as the overall Industrial group extrapolated for natural gas, source energy savings, electricity demand increase, and carbon reduction near and long term.

**Table 7. Energy savings and carbon reduction industrial heat pump estimates**



| **Unit Operations analyzed only** | Food, min. | Food, max. | Paper, min. | Paper, maxi. | Chemicals | Total, min. | Total, max. |
|---|---|---|---|---|---|---|---|
| Natural gas savings, TBtu/yr | 5.7 | 20.0 | 34.4 | 127.1 | 253.1 | 293.2 | 400.0 |
| Source energy savings, Tbtu/yr | 2.8 | 7.1 | 19.1 | 58.0 | 144.6 | 166.4 | 210.0 |
| Electricity consumption, MM kWh/yr | 288.0 | 1,263.2 | 1,500.0 | 6,750.3 | 10,595.4 | 12,383.3 | 18,609.0 |
| Electricity demand increase, MW | 32.9 | 144.2 | 171.2 | 770.6 | 1,209.5 | 1,413.6 | 2,124.0 |
| Heat pump output, MW | 152.6 | 535.3 | 921.9 | 3,402.8 | 6,773.1 | 7,847.6 | 10,711.0 |
| Carbon savings, near term carbon intensity, MTCe/yr | 0.2 | 0.5 | 1.1 | 3.7 | 8.4 | 9.7 | 12.6 |
| Carbon savings, long term carbon intensity, MTCe/yr | 0.3 | 0.9 | 1.6 | 5.7 | 11.6 | 13.4 | 18.2 |

**Sector-wide projection**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Natural gas savings, TBtu/yr | 20.0 | 72.0 | 48.0 | 179.0 | 684.0 | 752.0 | 935.0 |
| Source energy savings, Tbtu/yr | 9.7 | 25.4 | 26.6 | 81.7 | 390.8 | 426.9 | 490.9 |
| Electricity consumption, MM kWh/yr | 1,010.5 | 4,547.8 | 2,090.3 | 9,504.1 | 28,639.2 | 31,761.0 | 43,498.5 |
| Electricity demand increase, MW | 115.3 | 519.2 | 238.6 | 1,084.9 | 3,269.3 | 3,625.7 | 4,964.9 |
| Heat pump output, MW | 535.3 | 1,927.1 | 1,284.7 | 4,791.0 | 18,307.7 | 20,127.7 | 25,037.0 |
| Carbon savings, near term carbon intensity, MTCe/yr | 0.7 | 1.8 | 1.5 | 5.2 | 22.7 | 24.9 | 29.5 |
| Carbon savings, long term carbon intensity, MTCe/yr | 1.1 | 3.2 | 2.2 | 8.0 | 31.4 | 34.4 | 42.5 |

# Research, Development, and Deployment (RD&D) Needs

Our work and that of others (A2EP, Sintef, DryFiciency, and IEA Annex 58) applying IHPs to industrial applications highlights several areas for additional RD&D to advance deployment, application scale, and dispersion including the following.

## IHP DEMONSTRATIONS

A variety of IHP technologies need to be demonstrated in various industrial groups and process applications, along with the engagement of industrial, service, and engineering companies so they can partner on lowering adoption hurdles and gain insights into energy/carbon/nonenergy benefits. These demonstrations would benefit from third-party (DOE and National Labs) verification and communication of the cost and benefits. Standardized IHP designs that are integrated into common applications (e.g., food evaporation, drying) and supplement utility steam supply need widespread demonstration. Demonstration would also benefit from common field test procedures and performance measurement approaches to calculate and report key parameters (COP, lift) and document and communicate key parameters consistently and transparently.

IHP equipment supplier market development would benefit from more standardized base IHP componentry, modularization, and base case installation design and parameters, which could help deliver relatively low-cost IHPs for the market segment below 10 MW heat delivery. More importantly, the IHP supplier base within the United States is extremely limited: A summary of global IHP suppliers did not show one U.S. supplier (Arpagaus 2021). Accordingly, activities in the United States to cultivate IHP equipment suppliers and service providers are needed. Australia has been successful in attracting IHP equipment suppliers through a robust IHP promotion, demonstration, and deployment collaboration,[6] and the United States should follow similar strategies.

## IHP RANGE OF APPLICABILITY

To increase IHP energy savings and carbon reduction potential, IHP technology must be able to deliver heat at higher temperature (e.g., to 200°C) and lift heat without large capital cost (e.g., lift heat at 80°C at a cost of at most $900/kW heat delivered (Scheihing 2021)) for the advanced heat pumps to achieve a payback of five years or less (natural gas price = $5/MMBtus). A variety of R&D areas would enable these objectives:

- New vapor compression working fluids that can operate up to 200°C (heat sink temperature) with minimal environmental impact (GWP < 10)

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[6] J. Leak, Australian Alliance for Energy Productivity, pers. comm., October 2021.

- New innovative and optimized hybrid/compression: heat activated cycles to allow flexibility for varying source/sink/lift temperatures.

Any advanced IHP design must offer flexibility in retrofit versus new installation since industry operations can change over time. IHPs must be available in a variety of sizes, such as a small size < 100 kW for dedicated end use; a medium size at 500–2,000 kW for unit operations; and a large size at > 2,000 kW for utility steam heat delivery for entire processes and facility operations, for example, replacing or supplementing existing boiler house steam system. IHP designs that are modular would offer more flexibility in adaptation to industrial processes.

## IHP ECONOMICS AND DECARBONIZATION POTENTIAL

As mentioned, IHP technology adoption will be determined by several considerations, including the electric/natural gas price ratio, which influences the payback. Likewise, IHPs will need to compete with other process heating decarbonization technology choices, such as electric boilers, renewable fuels for boilers, combined heat and power, and solar thermal. IHP R&D must address lower capital cost without operational cost penalties (lower COP) to be competitive. Several other considerations need to be addressed, including the R&D areas noted below:

IHP Economics

- New IHP construction materials to enable lower IHP capital cost, especially in heat activated heat pump systems that cost < $900 per kW.
- New IHP designs that are system-integrated with advanced energy efficiency, initiatives and technologies (whole system optimization and control, CHP, waste heat, solar thermal, ground source)
- IHP designs for industrial parks and district heating/cooling: IHP heat and cooling/refrigeration co-sharing between neighboring facilities (industrial, commercial, and residential).

Economic performance could be extended to IHP carbon reduction potential in areas such as:

- Renewable heat and power supply integration: integrate IHPs with renewable energy generation technology, hot and cold energy storage, and dynamic load response/control.
- IHP application in conjunction with power generation and storage (electrical, thermal, chemical, and mechanical) technologies such as renewable hydrogen generation, gas-to-liquids, carbon capture, and storage.
- Further optimization and use of low GWP refrigerants.

## IHP KNOWLEDGE, TOOLS, AND CAPACITY BUILDING

Advanced IHP equipment designs, development of knowledge, information, and tools would assist in IHP scale and deployment including:

- State-of-the-art process-specific data in the industrial groups with significant IHP opportunity, including, chemicals, paper, food processing, and petroleum refining. Pinch analysis or other process integration methods to assess IHP fit needs should be further developed in cooperation with industry to create more accurate process data representative of current process technology.
- Workforce development: Basic informational technical material and training as appropriate to introduce mechanical and process engineers to the fundamental principles of IHPs would be valuable. Also, more advanced skills are needed, such as pinch analysis, process integration, and maintaining and optimizing IHPs. Industrial group-based, expert-level IHP training targeting process and utility engineers would educate key personnel responsible for modifying processes to save energy and decarbonize facilities.
- New software tools for IHP implementation would help energy engineers to assess IHP opportunities. Some pinch analysis tools are already available such as the IChemE (UK) and PinCH 3.2 (Lucerne University 2022) tools.
- Energy assessments to examine unit operation and plant-level IHP opportunities.
- University-based "Centers of Excellence for IHP Technology & Applications" would build knowledge and experience. European and Japanese IHP expertise is deep, and the United States could benefit from building similar technical expertise.

## COMPLEMENTARY CHALLENGES

IHPs face adoption challenges like those experienced by other electrification and emergent or transformative technologies. Additional study is needed to address these obstacles, which include:

- IHPs can replace a large component in an industrial process but sometimes not the whole system (e.g., meeting needs that were supplied by part of a steam system but not all of it). There is a need to understand how IHPs interface with whole system capacity and ways to increase the proportion of service provided.
- Research abroad has found that getting users involved in IHP deployment, integration, and optimization is essential and that how IHPs are used can influence the type of users (Martiskainen, Schot, and Sovacool 2021). This work also notes that in addition to providing incentives, policy should aim to mobilize users.
- Integration with systems upstream and downstream and the interface with lifetimes of equipment, economics, and reliability are needed.
- Integration research is also needed for hybrid systems such as IHP/solar thermal and IHP/thermal energy storage.

- R&D could aim to reduce mean time between failure to increase IHP reliability. R&D could provide a better balance of the use of novel technology and of time-tested and proven equipment, materials, and controls. This would help reduce IHP equipment downtime by supporting the industry with ease of repair and a widely available contractor base.

# Policy and Program Opportunities

IHPs face challenges that must be overcome to accelerate adoption, despite their benefits and the increasing strength of the drivers of their acceptance. These include categories illustrated in figure 22 and described further below.

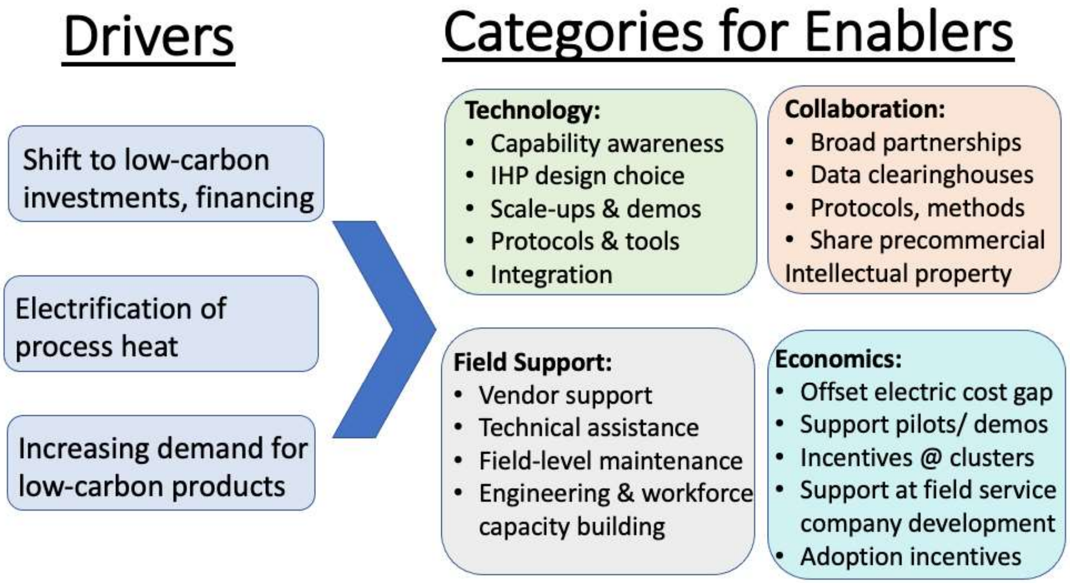

Figure 22. Enablers for IHP adoption

## ECONOMICS

This work shows that IHPs can have simple paybacks within the range of acceptability for industry when the natural gas price is high. However, as IHPs, especially those with higher temperature capabilities, are not widely used in the United States and industrial companies face uncertainties on capital, integration, and maintenance costs, economics will be a significant hurdle to adoption.

Policy can be a key enabler to address the electricity/natural gas price ratio. Multiple approaches could be considered to close the cost gap, including a cost of differences approach (CfD). This approach has been successful in addressing the higher starting cost of low-carbon technologies in the United Kingdom and Canada (Sartor 2019). Another approach would be incentives for utilities in the form of favorable electricity rates for beneficial electrification, where industry transitions from fossil fuels to low-carbon sources utilizing IHPs and other electric technologies. Incentives could also be considered for the places in the value chain that will be vital for success (e.g., adopters, vendors, third-party installers, and engineering and service companies).

Support for pilots and demonstrations at larger scale for IHPs can also play a role in lowering economic hurdles, as new knowledge will improve implementation and operational efficiency and identify value-returning nonenergy benefits.

## TECHNICAL

There needs to be increased awareness for industrial decision makers and plant engineers to understand that the capabilities of IHPs have advanced significantly in the last decade. Advances in understanding the choices for IHP type, working fluid (including choice of low GWP refrigerants), location of heat exchangers, and integration and control aspects are needed, as well as developments to accelerate electrification using increasing levels of low-carbon electricity while mitigating the variable aspects to delivering reliable electricity with quality that is similar to or better than that of baseload power.

Programmatic support and engagement with pilots and demonstrations at larger scale are key to address technical uncertainties and to minimize deployment risk. Agencies such as DOE and AMO can play a role helping with development of methods/protocols/evaluation tools, supporting the pilots, providing expertise to address scale-up and integration issues, providing test facilities at national labs, and facilitating partnerships across engineering, vendor, service, and industrial companies. Industrial clusters are a key opportunity for advancing IHPs as the market becomes concentrated: successes will be highly visible, and integration benefits can be leveraged across multiple players. As programs develop project portfolios for clusters or hubs, IHPs could be a key solution that addresses multiple objectives.

## PRODUCT AVAILABILITY

Currently the domestic supply of IHPs is quite limited. In the United States, Nyle Corporation sells IHPs for modest food dehydration and water heating applications with capabilities up to 72°C. Johnson Controls provides a range of IHP products in Europe, but they would need to be custom built in U.S. facilities. However, the upper temperature limit, heat pump thermal output (kW - MW), compressor and refrigerant capabilities, and flexibility of these domestic IHPs are limited. For example, commercial IHPs above 300–400 kW and with capabilities above 80°C are not available from U.S. vendors. Conversely, there are a wide range of IHP types and capabilities available from vendors in Japan and Europe with upper temperature limits to 160°C, several MW, and a wide range of compressor and refrigerant choices (Arpagaus 2021). To develop a domestic market for IHPs and suppliers we should encourage global suppliers to support pilots and large-scale demonstrations in the United States. Encouraging suppliers to be aware of these U.S. pilots and to participate in efforts to lower hurdles is a path towards establishment of domestic supply, and preferably manufacturing capabilities for IHP equipment and service support. Policy support for the pilots, demonstrations, and early adoption would significantly help to accelerate progress.

## FIELD SUPPORT

Field-level support is needed so a cadre of organizations can help with these activities and foster development of capabilities and expertise that support the ongoing maintenance and optimization of equipment. Pilots and demonstrations can be a starting point providing clarity on needs, but from history with earlier IHPs and recent experience accelerating adoption of IHPs in Australia, Europe, and New Zealand, it is clear that a domestic capability for field-level support needs to be developed. The drivers for establishing domestic chain capabilities include the need for local service of IHPs (reliability is crucial), trained and experienced process engineers to work directly with end-users on integration and optimization questions, and expertise to design new process implementations.

This is a prime area for workforce development and training. National labs and agencies could help provide training curricula. Engagement with the pilots and demonstrations is a good starting point to develop expertise, but a strategy for capability development is needed that could support field level installation, maintenance, and further optimization.

## COLLABORATION

Collaborations across industry partners, academics, national labs, and government agencies can be key to the success of demonstrations at scale for emerging and transformative technology. Data and learnings from those demonstrations need to be visible for the end-user community to readily adopt IHPs, which is where data clearinghouses can help, along with the development of standard design and field-testing methods, protocols, and metrics. The development of commonly recognized protocols and methods (e.g., for evaluation of COP) would be very helpful to lower communications barriers.

# Recommendations

Field-level studies are a key next step to spur an IHP user community, accelerate learning, lower barriers, and scope additional applications. Key recommendations include the following.

## INDUSTRY

- Probe the application aspects of this work and engage in conversations during field demonstrations and/or pilots with IHP vendors and local engineering service firms.
- Discuss with international vendors prospects for IHP applications in the United States to stir the market and probe integration issues.
- Consider which potential IHP applications would provide the greatest benefits/costs.

## UTILITIES

- Discuss with industrial customers and local engineering service firms where IHPs could provide benefits.
- Probe the demand response attributes of IHPs.

- Engage with partners to support pilots and/or demos, potentially at industrial clusters where there are shared learning opportunities.
- Work with industry and policymakers to describe what is needed for expanding the ability of industry to use variable electricity (e.g., from wind or solar).
- Provide incentives such as rates that encourage adoption of IHPs by end-users by defraying the price differential between electricity and natural gas, use of electric technologies, active use of curtailed energy, and education to encourage effective use of demand response approaches).

## POLICYMAKERS

- Develop policy enablers to accelerate the demonstration of IHPs at increasing scale at industrial facilities.
- Seek ways to offset the difference in electricity/natural gas prices, perhaps by a contract for differences approach, to accelerate adoption.
- Encourage increased product availability, developing an understanding of obstacles and working with domestic manufacturers, foreign manufacturers, importers, and others to address these obstacles.
- Devise incentives for engineering service firms to build IHP expertise, a qualified workforce to design and service IHP applications, and routes to spur engagement in user communities.
- Support infrastructure expansion for providing more variable electricity to industry and provide support to defray the higher price of electricity versus natural gas to spur investment of electric technologies such as IHPs.

## FEDERAL/STATE AND RD&D AGENCIES AND COLLABORATIVES

- Educate federal and state policymakers on IHP technology and benefits, as European IHP technologists have informed EU policymakers (De Boer et al. 2020).
- Accelerate IHP demonstrations at increasing scale at industrial facilities.
- Study further technical details in actual field applications to screen for IHP potential at the manufacturing process level. Process design studies on steam and other process heat, pilots, and/or with techno-economic studies in partnership with industry, IHP providers, and service companies are needed.
- Design metrics, standards, evaluation tools and protocols to clarify how IHP performance is evaluated in industrial applications and communicate case study results.
- Engage on advancing IHP technology, materials, and working fluids that allow higher temperature IHPs, improving reliability and performance, while reducing or maintaining IHP capital cost.
- Participate in international research collaboratives to promote technology transfer of advanced IHP concepts (e.g., leverage European and Japanese IHP technical expertise).

- Support academic institutions to build IHP technical expertise and establish research programs to build engineering workforce trained in IHP fundamentals.

# Summary and Conclusions

IHPs have significant potential for reducing energy and $CO_2$ emissions across the industrial sector, with particular applicability to the paper, food, and chemicals sectors where there are significant proportions of process heating needs requiring relatively low temperature (60°C to 200°C). Our research found:

- IHPs were typically able to save 26–32% of the source energy used for process heat generation.
- The vapor compression type IHP decreases in natural gas use were typically 2.7–3.7x the increases in electricity use across all unit operations. Similarly, the $CO_2$ reductions from natural gas savings were 3.5–4.7x the $CO_2$ associated with electricity use.
- Simple paybacks for the compression type IHPs were near or less than three years at a natural gas price of $4.50/MMBtus.
- Although the energy savings potential for heat activated type IHPs was lower than vapor compression heat pumps for the applications studied, as the technology advances and more opportunities are pursued for reusing waste heat between 60°C and 250°C there is a strong potential for these IHPs to have greater impact due to their flexibility.
- Across all unit operations, the IHP analyses showed the potential to:
    - Reduce process heat energy 293–400 TBtus/year (42–57%) of the 704 TBtus/year of process heat energy in the subsegments analyzed for the economic and economic + technical cases, respectively. A large portion (58%) of this reduction comes from potential application of IHPs in ethanol production.
    - Reduce $CO_{2e}$, 9.7–12.6 MMT $CO_{2e}$/year, which is equivalent to the emissions from 2.1–2.7 million passenger cars/year.
        - With lower emissions factors for grid produced electricity by 2050, the reductions potential would be 13.4–18.2 MMT $CO_{2e}$/year.
    - Expansion of IHP use across the far greater breadth of industry would save even more energy and $CO_2$ emissions.

The relationship between electricity and natural gas prices influences the economics for IHP application. Our study found that where the ratio of electricity/natural gas price is less than 3 there are simple paybacks that would already meet the bar of cost effectiveness for several IHP types. In states where this ratio is greater than 3, the need for incentives to accelerate IHP adoption is even greater.

We also found that several factors influence adoption by the industrial customer, including economics, technical risk, integration challenges, and local capabilities for maintenance. Enabling policies and programs by government and utility programs would accelerate IHP adoption. This work also shows that IHPs can be a key technology in aiding beneficial electrification in parallel with the grid moving to a higher proportion of low-carbon generation capabilities.

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# Appendix A. IHP Types

Six IHP types were considered in this work for optimum fit within any process.

Mechanical vapor compression (MVC), closed cycle

Mechanical vapor recompression (MVR), semi-open cycle

Mechanical vapor recompression (MVR), open cycle

Thermal vapor recompression (TVR), open cycle

Heat activated Type 1 (HA Type 1), closed cycle

Heat activated Type 2 (HA Type 2), closed cycle

These types are shown in figure A1. A brief description of each IHP type with their pros and cons is listed in table A2. These types are illustrative of process types and not meant to be comprehensive. They are described and illustrated briefly below.

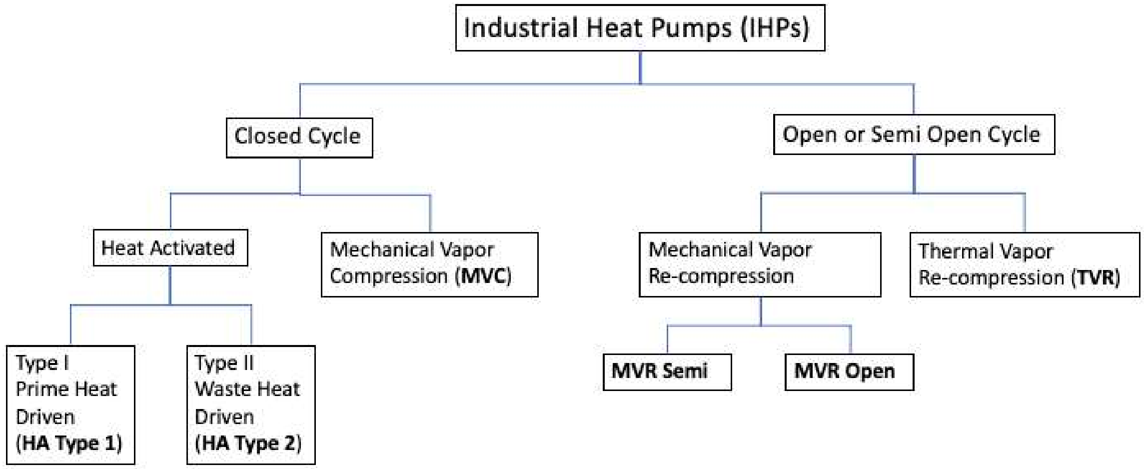


**Figure A1. Illustration of IHP types. Adapted from Gluckman and McMullan 1988.**

## MECHANICAL VAPOR COMPRESSION (MVC), CLOSED CYCLE

The MVC heat pump relies on a refrigerant loop, which could vary widely. A key thermodynamic property of the MVC refrigerant is the critical temperature of the fluid. The fluid will also have a lubricant to allow the heat pump compressor to operate. Both the refrigerant critical temperature and the lubricant properties will set the upper temperature of the MVC heat pump. It requires a heat exchanger on both the cold side (evaporator) and hot side (condenser) and therefore additional lift temperature must be provided to accommodate the heat source and sink heat exchanger temperature drop (delta T) to lift the heat. Figure A2 shows the MVC heat pump.

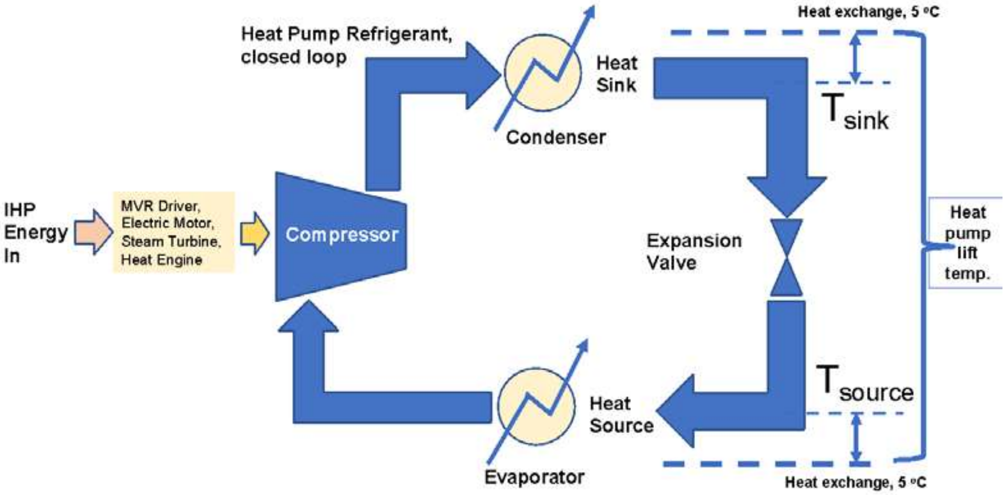


Figure A2. Mechanical vapor compression, closed cycle heat pump

## MECHANICAL VAPOR RECOMPRESSION (MVR), SEMI-OPEN AND OPEN CYCLE

The MVR heat pump has been applied in various industrial operations. It typically will take advantage of recompressing waste low-pressure steam, such as in a dairy processing plant or pulp mill, or capturing a process fluid, such as hydrocarbons in a petrochemical plant or refinery that would otherwise be condensed and heat transferred to the atmosphere. Typically, the compressor will be driven by an electric motor, but a heat engine (steam turbine) could serve as the prime mover. The difference between the semi-open and open cycle is a heat exchanger used for the semi-open cycle system to separate waste vapors from the new process steam or other fluid (figure A3). In the open cycle the waste vapors are reinjected directly back into the process without heat exchange.

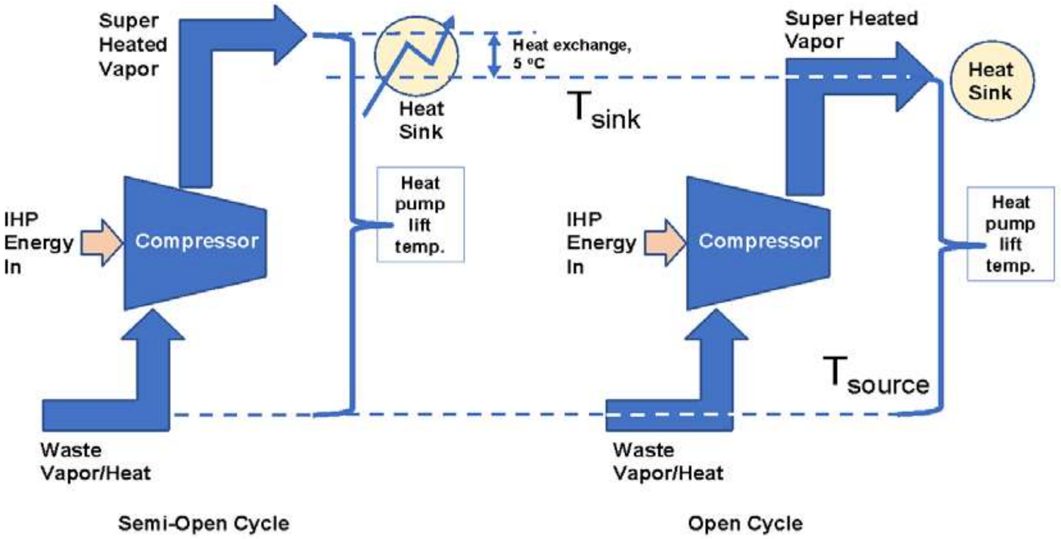


Figure A3. Mechanical vapor recompression (MVR), semi-open and open cycle

## THERMAL VAPOR RECOMPRESSION (TVR), SEMI-OPEN CYCLE

The TVR heat pump is perhaps the most common in industry today, although it is typically not characterized as a heat pump by industrial facility personnel. It is the simplest type as it has no moving parts, but it is restricted to pumping heat from a steam waste heat source to a steam heat supply requirement (heat sink). The TVR works by injecting higher pressure steam, typically at medium pressure (e.g., 200 psig), into the steam ejector, which induces the low-pressure waste steam into a mixed stream, resulting in an intermediate steam pressure (figure A4). The TVR system is low cost but will only make sense for applications that require steam saturated temperatures be lifted 20°C or less (waste steam to process steam requirement). Appendix D further explains TVR applications and limitations.

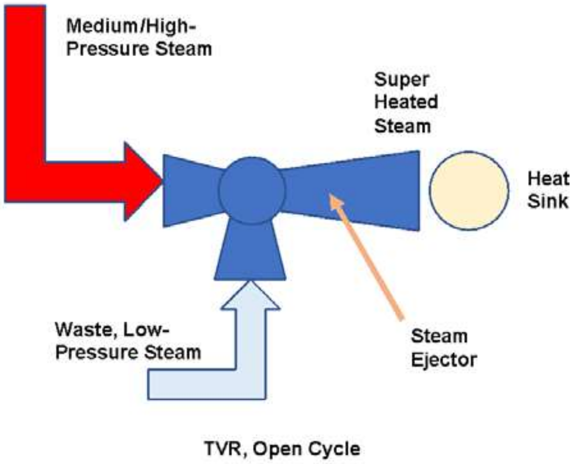


**Figure A4. Thermal vapor recompressor, open cycle**

## HEAT ACTIVATED TYPES 1 AND 2, CLOSED CYCLE

The heat activated (HA) heat pump technology can be designed to work by various chemical processes, such as absorption, adsorption, or reversible chemical reaction. The common thread in these systems is that the heat pump cycle is predominantly heat activated, unlike vapor compression heat pumps. However, they do require a small amount of electricity for pumping the working fluids. Figure A5 shows a comparison of the HA Types 1 and 2 heat pump concepts.

The HA Type 1 design requires a supply of prime heat at a temperature above the sink temperature to lift the waste heat from the source temperature to the sink temperature.

The HA Type 2 design is waste-heat driven: For approximately two units of waste heat delivered to the heat pump, one unit is lifted up to the sink temperature and one unit is dropped to the ambient temperature, requiring enough driving force between the source heat and ambient temperatures. As a rule, the HA Type 2 heat pump can lift heat 80% of delta T of the source heat and ambient temperature.

The HA heat pumps are more capital intensive than the compression heat pumps (MVC and MVR) and the TVR heat pump. As mentioned, one of their advantages is lower electricity requirements. In our analysis, we have assumed that 4% of the heat sink's energy is required for electrical energy to circulate the HA's working fluid.

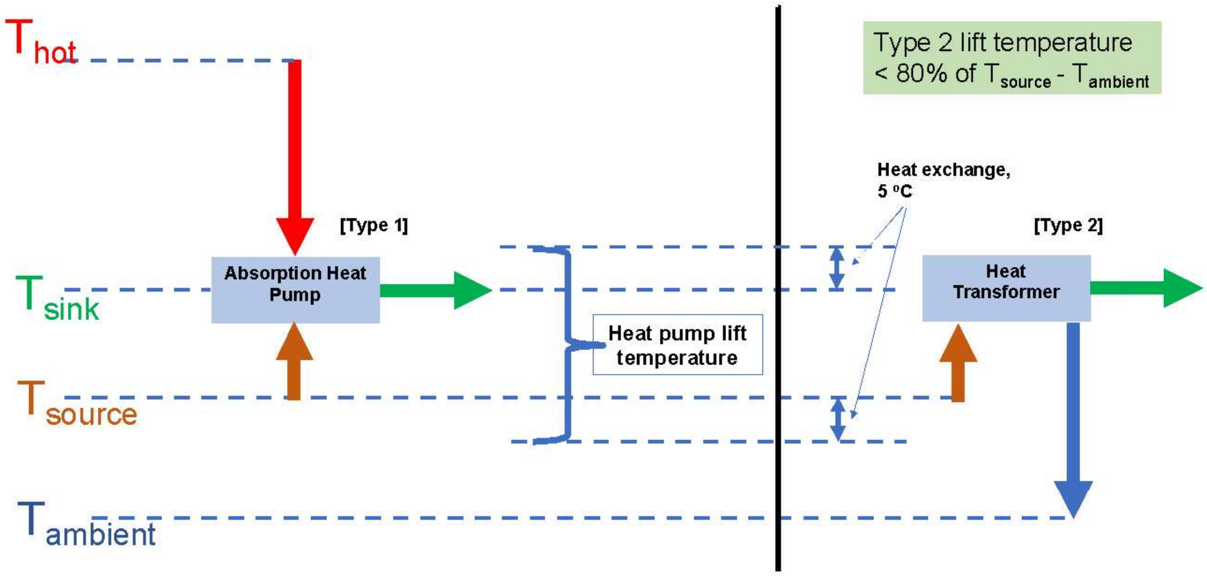


Figure A5. Heat activated Types 1 and 2 heat pumps

## IHP ENERGY PERFORMANCE

The energy performance of any of the six IHP types are determined by the type of IHP driver energy ($E_{driver}$) and the coefficient of performance (COP).

$COP = Q_{sink} / E_{driver}$

$Q_{sink} = Q_{source} + E_{driver}$

$COP = COP_{Carnot} * IHP_{Carnot\ efficiency}$

Table A1 summarizes the assumed characteristics and COP equations that determine the energy performance of each of the six IHP types.

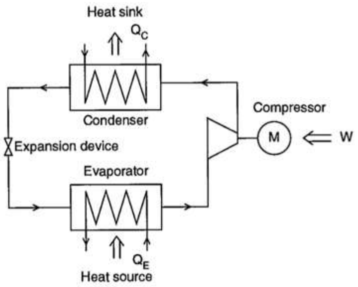
**Table A1. IHP energy performance characteristics**

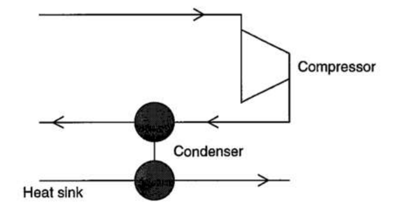
| IHP type | $E_{driver}$ type | $COP_{Carnot.}$ (T in absolute temperature, K) | IHP Carnot efficiency assumed |
|---|---|---|---|
| MVC, closed cycle | Electricity, electric motor, shaft power | $\frac{(T_{sink}+DX^{1})}{[(T_{sink}+DX)-(T_{source}-DX)]}$ | 50% |
| MVR, semi-open cycle | Electricity, electric motor, shaft power | $\frac{T_{sink}}{[T_{sink}-(T_{source}-DX^{1})]}$ | 50% |
| MVR, open cycle | Electricity, electric motor, shaft power | $\frac{T_{sink}}{[T_{sink}-T_{source}]}$ | 50% |
| TVR, open cycle | Medium/High-pressure steam | $\left[\frac{(T_{sink}+DX)}{[(T_{sink}+DX)-(T_{source}-DX)]}\right]*\left[\frac{[(T_{steam}-DX)-(T_{source}-DX)]}{(T_{steam}-DX)}\right]$ | NA |
| HA Type 1, closed cycle | Prime heat, steam or process heat | $\left[\frac{(T_{sink}+DX)}{[(T_{sink}+DX)-(T_{source}-DX)]}\right]*\left[\frac{[(T_{steam}-DX)-(T_{source}-DX)]}{(T_{steam}-DX)}\right]$ | 70% |
| HA Type 2, closed cycle | Waste heat | $\left[\frac{(T_{sink}+DX)}{[(T_{sink}+DX)-(T_{amb.}+DX)]}\right]*\left[\frac{[(T_{steam}-DX)-(T_{amb}+DX)]}{(T_{source}-DX)}\right]$ | 70% |

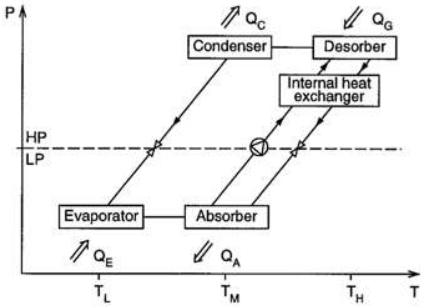
1 - DX = delta T across heat exchanger, assumed 5°C; closed cycle has heat exchanger on heat source and sink, semi-open cycle has heat exchanger on heat source only, and open cycle has no heat exchangers.

Table A2 lists the pros and cons for the six IHP types.

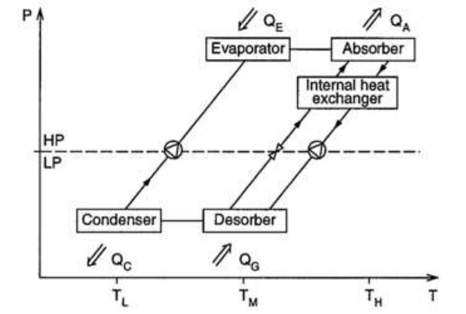
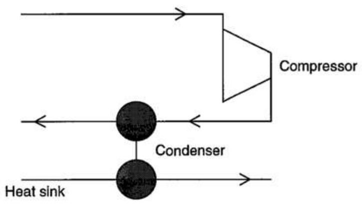
**Table A2. Description of industrial heat pump types**

<table>
<tr><th>IHP type</th><th>Description</th><th>Pros</th><th>Cons</th></tr>
<tr><td>Closed cycle, mechanical vapor compression (MVC)</td><td>


</td><td>Good COP for moderate lift temperature (< 40 °C)<br>Multiple vendors<br>Replaces onsite steam or direct fired process heat</td><td>Requires low IHP lift temperature and/or low E/NG price ratio (< 3–5)<br>Limited supply temperature to 160 °C</td></tr>
<tr><td>Open or semi-open cycle mechanical vapor recompression (MVR, semi-open, and open)</td><td>


</td><td>Good COP for moderate lift temperature (< 40 °C)<br>Electricity only on site<br>High volume flow compressor to compress steam<br>Can be combined with a closed cycle MVC</td><td>Requires low electric-fuel price ratio<br>High speed compressor</td></tr>
<tr><td>Closed cycle heat activated (or sorption), Type I, prime heat-driven, Absorption heat pump (IEA 1995) (HA Type 1)</td><td>


</td><td>Uses lower cost fuel or steam as driver<br>Minimal moving parts<br>Higher supply temperature ~200 °C</td><td>High CapEx<br>Large footprint required<br>Limited vendors<br>Emerging technology</td></tr>
</table>

| IHP type | Description | Pros | Cons |
|---|---|---|---|
| Closed cycle heat activated (or sorption), Type 2, waste-heat-driven, heat transformer heat pump (IEA 1995)<br>(HA Type 2) |  | Uses waste heat as driver<br>Minimal moving parts<br>Higher supply temperature ~200 °C | High CapEx<br>Large footprint required<br>Limited vendors<br>Emerging technology<br>Requires adequate temperature drop from waste heat to ambient |
| Open or semi-open cycle mechanical vapor recompression (MVR, semi-open and open) |  | Good COP for moderate lift temperature (< 40 °C)<br>Electricity only on site | Requires low electric-fuel price ratio<br>High speed compressor |

# Appendix B. IHP Economics and Capital Cost Parameters

Capital cost estimates for the six IHP types are shown in table B1. The MVC capital cost (CapEx) for the economic scenario is based on values from previous research (Arpagaus 2020), but we raised the CapEx to account conservatively for added design and installation costs. Likewise, with the MVR systems we referenced previous research (De Boer et al. 2020) and increased CapEx as we did for the MVC estimate. For the TVR CapEx estimate, TVR vendor data and the total installed cost for a specific end-user TVR installation informed our estimate. The HA Types 1 and 2 CapEx estimates referenced estimates from previous research (QPinch 2021) and experience with absorption technology (lithium-bromide, ammonia-water systems). We increased the capital cost for the technical scenario over the economic scenario by at least 50% to account for an added stage of compressors in the MVC and MVR application and added complexity with all heat pump systems. For the technical scenario, the TVR heat pump technology is not applicable since the IHP lift temperature is not possible or practical.

**Table B1. Capital cost estimates for the six IHP types for economic and technical scenarios.**

| IHP type | Economic scenario capital cost, \$U.S./$Q_{sink}$ (kW) | Technical scenario capital cost, \$U.S./$Q_{sink}$ (kW) |
|---|---:|---:|
| MVC, closed cycle | 400 | 800 |
| MVR, semi-open cycle | 325 | 650 |
| MVR, open cycle | 250 | 500 |
| TVR, open cycle | 150 | NA |
| HA Type 1, closed cycle | 1,000 | 1,500 |
| HA Type 2, closed | 1,250 | 1,875 |

## IHP ENERGY SAVINGS AND SIMPLE PAYBACK

The energy savings and simple payback were calculated for both the economic and technical IHP scenarios. The energy savings from both scenarios are additive, therefore, two or more IHPs are required within the same unit operation to reach the full IHP technical potential.

The economics of the IHP are greatly influenced by the IHP lift temperature, which determines the IHP energy in, and thus the IHP operating cost, as well as the prime fuel consumption that is avoided: the energy saved. We used simple payback (PB) as a measure of IHP economics.

PB is determined by the capital cost of the IHP ($IHP_{capex}$) and the IHP net energy cost savings, $IHP_{savings}$:

PB = $IHP_{capex}$ /$IHP_{savings}$.

$IHP_{capex}$ is listed above in table B2.

$IHP_{savings}$ = IHP net fuel savings – process heating cost avoidance (savings) – IHP operating cost – IHP maintenance cost.

IHP net fuel savings = heat pump natural gas cost savings – heat pump electricity operating cost.

The process heating cost avoidance is determined through the pinch analysis and specifically by the change in "hot utility" demand (MMBtus/ton product) as described in the Annex, section 1.

Process heating cost avoidance = [IHP Heat Sink (MMBtus/ton) / [combustion efficiency (%)/100] * IHP annual operation (hours/year) * [fuel cost ($/MMBtus) + fuel combustion added cost ($/MMBtus)].

Combustion efficiency was assumed to be 80%.

IHP annual operation was assumed to be 8,760 hours per year. This is an upper bound; fewer hours would lengthen payback periods.

Fuel cost was varied in the economic analysis at $3.00, $6.50, and $10.00 per MMBtus.

The fuel combustion added cost, beyond the energy fuel cost, was assumed to be a fixed cost at $2.00 per MMBtus. It accounts for the cost of emissions control, steam condensate loss, boiler steam water treatment, and boiler or process heater maintenance costs.

IHP operating cost = IHP Energy In (kWh/ton) * IHP annual operation (hours/year) * electricity cost ($/kWh) /production rate (tons/year).

IHP maintenance cost varied from 1–3% of $IHP_{capex}$ per year based on the type of IHP, as in table B2.

**Table B2. Maintenance cost factor for six IHP types**

| IHP type | Maintenance cost (% of IHP CapEx) |
|---|---|
| MVC, closed cycle | 3 |
| MVR, semi-open cycle | 3 |
| MVR, open cycle | 3 |
| TVR, open cycle | 1 |
| HA Type 1, closed cycle | 2 |
| HA Type 2, closed | 2 |

The overall unit operation Btu % energy savings resulting from the IHP heat pump =

$IHP_{\text{Btu savings, economic}}$ + $IHP_{\text{savings, technical}}$ /Unit operation total site energy consumption * 100 (%)

$IHP_{\text{Btu savings, economic}}$ = Qsink (MMBtus/ton product) in economic IHP scenario

$IHP_{\text{Btu savings, technical}}$ = Qsink (MMBtus/ton product) in technical IHP scenario

# Appendix C. Emission and Carbon Intensity for Energy

The carbon intensity of the electrical grid and natural gas energy used were obtained from the EIA for 2020. We used a projection of carbon intensity values to 2050 as a reference for anticipating future values as the electrical grid becomes further decarbonized, as shown in table C1. With many states setting aggressive grid decarbonization goals recently, more aggressive factors were used than in the EIA projections.

**Table C1. Emissions factors for carbon**

| | Carbon emissions factors | | |
|---|---|---|---|
| | 2020* | 2035 | 2050 |
| Natural gas,<br>metric tons $CO_2e$/therm | 0.005 | 0.005 | 0.005 |
| Electricity, metric tons $CO_2e$/kWh | 0.0004 | 0.00025 | 0.0001 |

*** Based on EIA numbers for 2020. For 2035 and 2050 more aggressive carbon factors were chosen.**

**Source: Adapted from EIA 2021c.**

# Appendix D. TVR Applicability

The thermo vapor recompression (TVR, thermocompressor) is limited to operations that require certain operating conditions to be satisfied between the heat sink and heat source temperatures for different working fluids. Additionally, the driving heat (e.g., temperature) also has a strong impact on the COP of the TVR. In this IHP report, TVRs are limited to steam as the working fluid and thus further constrain the cost effectiveness and potential TVR applications where there is an open cycle steam-to-steam system IHP.

Some of the most common applications or areas in industry where TVRs are used to capture and recover the steam are:

- Very-low-pressure (almost atmospheric) steam is vented
- Steam vapors are sent to the surface condenser after the last stage of a unit operation (multi-effect evaporator)
- Condensate flashing steam

There are thermodynamic constraints and design limitations that come into effect with a simple TVR. The main thermodynamic constraint is the compression ratio: the ratio of the absolute discharge pressure to the absolute suction pressure, which limits the amount of temperature lift in the TVR. Most manufacturer’s design data limit TVR applications with steam to less than 20°C temperature lifts, with the heat source as atmospheric pressure steam typical of vented steam, condensate flashing steam. That same design data limit TVR applications with steam to temperature lifts of less than 15°C, with the source being sub-atmospheric pressure steam typical of process steam at the end of the unit operation (multi-effect evaporator) headed to surface condensers, that is, fin-fans.

Due to this temperature lift constraint, and the heat source being atmospheric and sub-atmospheric steam, TVRs see applicability only in the economic potential cases that are evaluated in this report. Even then, several economic potential cases presented in this report may require a higher lift temperature and a complex design or a multi-stage TVR. Technical potential cases require much higher temperature lifts and a significantly complex TVR system as well as multiple driving sources of steam that reduce the overall IHP COP and negate all benefits of the TVRs for both energy savings and carbon emissions. Hence, TVRs were not considered to be part of the IHP solution in the technical potential cases.

It is clear that the TVR application becomes restrictive among all the different IHP economic and technical potential cases considered in this report. Nevertheless, the simplicity of the TVR—having both the smallest capital cost of all the IHP technologies available today and having no moving parts, implying negligible maintenance expenses—deserves consideration when evaluating IHP applications. We encourage direct communication with any of the TVR manufacturers in describing the IHP application, which would provide valuable information on whether the TVR will be a suitable option for that specific IHP application in industry.

# Appendix E. Heat Activated (HA) Type 1 and Type 2 Efficiency

This report uses an optimistic 70% as the Carnot efficiency possible for the actual COP achievable by the IHP types, HA Type 1 and HA Type 2. This is debatable; the reader can choose to reduce that Carnot efficiency number to 50%, which is the assumption used to arrive at the actual COP for the other electrically driven IHP types: MVC, MVR Semi, and MVR Open.

The calculation of the COP in a IHP is specifically and heavily dependent on the source and sink temperatures. In this report, these temperatures were chosen so that the source temperature always represented the lowest temperature of any available heat while the sink temperature always represented the maximum temperature of the heat delivered to a process. This is automatically the case when an electrically driven IHP is used with a pure working fluid because the heat transfers at the source and sink happen at a constant temperature (evaporation and condensation). Nevertheless, depending on the actual application in the process, most applications may have a sensible temperature glide, which could be a huge advantage in a heat activated IHP as there is a significant glide in the heat given out or absorbed due to the working fluids concentration differences. The net result of this temperature glide allows for a much lower effective lift compared to the electrically driven IHP. Since it was very difficult to identify each specific situation in all the cases considered here in this report, we decided to compensate the heat activated IHP with a higher Carnot efficiency rather than calculating the actual COP with the specific temperature glides of the application.

We believe that the heat activated IHPs have not been pushed to their performance limits given their limited applications, few manufacturers, and lack of understanding by the industry. Combined with the advent of extremely sophisticated heat exchange technology, the heat activated IHPs also allow for a higher internal heat exchange between the hot and cold streams. Hence, the higher Carnot efficiency used in this report could be justified given the standard calculation of the ideal COP with fixed sink and source temperatures and assuming no internal heat recovery per se. Lastly, with no moving parts such as a compressor, the heat activated IHP’s performance does not degrade significantly with varying loads, while the isentropic efficiency of the compressor would surely see a significant variation with load and thus a direct impact to the system’s COP. We note that there are several advances in the compressor technology, including variable speed drives, that can allow for a relatively high level and constant compressor isentropic efficiency.

# Appendix F. Rationale for Excluding Select Unit Operations from the Technical Scenario

The authors were sensitive to the stream data (temperatures and heat duties) in each of the unit operations as well as the limitations of the IChemE Pinch Analysis software tool. The concerns ranged from the validity of the data to the general applicability of these data in each industrial group. The data used for the unit operations pinch analysis were dated (probably early 1990s), and the unit operations may have undergone significant changes. Whenever it was questionable to implement IHPs, the IHP was not evaluated in that specific case. This situation occurred in three different unit operation cases, all technical scenarios: ethylene debutanizer reboiler; ethylene water stripper reboiler; and non-integrated paper mill pulper.

In the ethylene unit operations case, two IHPs were implemented: the first between the quench water (source) and the debutanizer reboiler (sink) and the second between the quench water (source) and the water stripper reboiler (sink). These were both economic scenarios and were found to be excellent applications for IHPs. Additional technical scenario IHP opportunities clearly exist, but that analysis will require a much more sophisticated and higher-fidelity level of the pinch analysis tool than used for this report. We could have made certain assumptions with the stream data as well as with the IChemE pinch analysis model and identified significant technical IHP opportunities in the ethylene industrial group, but did not feel confident that we could provide a solid basis and foundation for such analysis.

In the non-integrated paper mill pulper unit, there were five different data sets that were evaluated for pinch analysis and an IHP economic scenario was implemented in each of the five different data sets. Based on the stream data descriptions, it was unclear if implementation of additional IHP opportunities was actually feasible. We believe that there could be significant IHP opportunities in the paper drying process but, given the data sets and their validity, refrained from undertaking the technical IHP scenario in the non-integrated paper mill pulper unit operations.

Lastly, both IHP economic and IHP technical analysis scenarios were terminated when the pinch temperature moved significantly (>25°C) and when the sink temperatures were higher than 150°C.

The ethyl alcohol, ethanol fuel sub-industrial group was the fourth unit operation where only an economic potential case was evaluated. It was also the only sub-industrial group in which the IChemE pinch analysis tool was not applied, due to a lack of adequate hot and cool stream data to perform pinch analysis. However, there was an alternative approach to evaluate IHP potential using energy intensity data from literature on the distillation tower, which removes water from the 85% water/15% ethanol mixture downstream of the fermentation process. Sufficient data existed to analyze the six IHP types pumping heat from the distillation tower’s condenser heat (source) to the reboiler where steam is normally supplied (sink), but only for the economic potential case.

# Appendix G. Pinch Analysis

One of the principal tools is the representation of composite curves of heat flow in the system to determine the minimum energy consumption target for a given process. This includes generation of a composite curve, where the profiles of process heat availability (heat sources or hot composite curve) are combined with the heat demands (heat sinks or cold curve). The degree of overlap provides a measure of the potential for heat recovery, and where the curves most closely approach each other is called the "pinch point," as shown in figure G1. The pinch point temperature divides the hot and cold streams that are exchanging heat with each other into two separate parts. Above the pinch point there is a heat deficit and below the pinch point there is a heat excess. Optimum placement of the IHP would be to pump heat from below to above this pinch point.

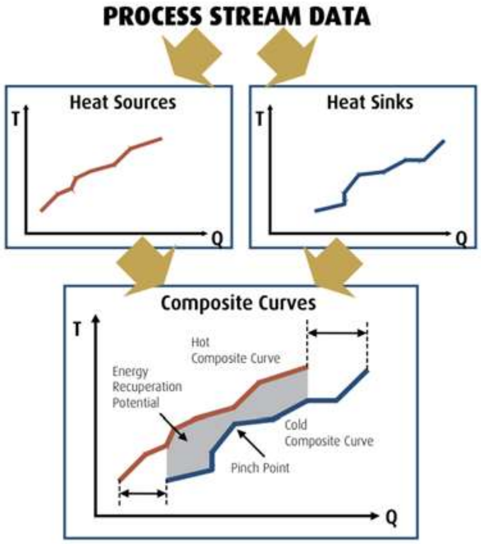


Figure G1. Illustration of the grand composite curve and pinch point. Source: NRCan 2003.

EXHIBIT MR-3

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

September 2016

# Field Demonstration of Ground-Source Integrated Heat Pump - Final Report

## Principal Investigator: Van Baxter

Prepared for the U.S. Department of Energy
By:

Van Baxter
Jeffrey Munk
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Oak Ridge National Labortaory

The Department of Energy’s technology demonstrations are conducted in cooperation with the General Service Administration’s Green Proving Ground program. The Green Proving Ground leverages GSA’s real estate portfolio to evaluate innovative sustainable building technologies and practices, while the Department of Energy-funded technology demonstrations are conducted in both federal and non-federal buildings. Findings are used to support the development of GSA and DOE performance specifications and inform decision-making within federal agencies and the real estate industry. The programs aim to drive innovation in energy and environmental performance in buildings and help lead market transformation through deployment of new technologies. Learn more at GSA.gov/GreenProvingGround and CommercialBuildings.energy.gov/TechDemo

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Energy and Transportation Science Division

# Field Demonstration of Ground-Source Integrated Heat Pump – Final Report

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September 2016

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under contract DE-AC05-00OR22725

## Preface

This is the last of two reports for the Ground-Source Integrated Heat Pump (GS-IHP) demonstration project.

Report 1: *Field Demonstration of Ground-Source Integrated Heat Pump – Part I. Technology and Field Demo System/Site Descriptions, and Preliminary Summer/Fall Performance Analysis for One Site.*
This volume provides detailed descriptions of the two test sites and the GS-IHP demonstration system. One was located in Knoxville, TN and the second in Oklahoma City, OK. Both are in the small commercial category (under 10,000 $ft^2$ floor space). A description of the GS-IHP technology is also provided along with details of the measurement and performance analysis plans. Due to a protracted construction schedule for the Oklahoma City site, this report only includes preliminary summer/fall performance data and analysis for the Knoxville site.

Report 2: *Field Demonstration of Ground-Source Integrated Heat Pump – Final Report*
This second volume provides cooling, heating, and spring season performance comparisons for the GS-IHP vs. the baseline in the Oklahoma City location. It also summarizes annual performance of the test system in Knoxville with comparisons vs. the baseline. A cost-effectiveness analysis of the GS-IHP vs. the baseline is included.

## Contents

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# I. Executive Summary

Reducing energy consumption in buildings is key to reducing or limiting the negative environmental impacts from the building sector. According to the United States (U.S.) Energy Information Administration (EIA), in 2013, commercial buildings consumed 18.1 quads of primary energy, which was 18.6% of the total U.S. primary energy consumption. The primary energy consumption in the commercial sector is projected to increase by 2.8 quads from 2013 to 2040, the second largest increase after the industrial sector. Further space heating, space cooling, and ventilation (HVAC) services accounted for 31% of the energy consumption in commercial buildings.

Small commercial buildings (≤10,000 $ft^2$ floor space) represent about 21% of the commercial floor space in the United States. Many such buildings (and defined spaces within larger commercial and institutional buildings) also have significant domestic hot water (DHW) loads, such as restaurants, laundry facilities, health & fitness centers, etc. The all-electric subset of small commercial buildings consumes approximately 0.160 Quads of primary electricity energy annually for HVAC and WH services.

More than half of U.S. commercial building space HVAC needs are provided by packaged HVAC equipment, mostly rooftop units (RTU; cooling only or heat pump types) with less than 50 tons of cooling capacity. RTUs are popular because they are inexpensive, provide zonal control, are easy to install, and can be serviced without disrupting occupants. Given their advantages, their large market share will likely continue. DHW loads in small commercial buildings are predominantly met by either electric or gas storage water heaters (WH).

Today's RTUs are inefficient for a host of reasons. Many are oversized to handle peak ambient temperatures. Capacity is also wasted by over-drying indoor air in dry climates. Single-speed blowers run for ventilation during all occupied hours, using about half of annual rooftop unit energy. Improving their operational efficiency is essential for enhancing overall commercial building energy performance.

Conventional storage WHs, particularly electric WHs, are approaching thermodynamic limits to their efficiency potential. Storage WHs of the type used in small commercial buildings are subject to Department of Energy (DOE) minimum efficiency requirements. For instance, 50 gallon electric WHs manufactured after April 15, 2015 must have an energy factor (EF, an annual efficiency metric) of ≥0.94. Significant increases in WH efficiency will need to come from use of heat pumping technologies; either combined or integrated heat pumps (IHP) or standalone heat pump water heaters (HPWH).

ClimateMaster, Inc. (CM) and Oak Ridge National Laboratory (ORNL) jointly developed a new, highly efficient electric integrated HVAC and water heating (WH) system – the ground-source integrated heat pump (GS-IHP). The new GS-IHP system is a combination of a very highly efficient variable-speed (VS) water-source heat pump (WSHP) capable of space heating and cooling and domestic water heating coupled to a geothermal energy source/sink. Most often the geothermal source/sink is a closed-loop ground heat exchanger (GHX loop). The GS-IHP system was developed primarily for residential buildings and is expected to reduce space heating/cooling energy use by ≥50% and WH energy use by ≥75% for that application compared to minimum efficiency electric heat pump and WH systems. GS-IHPs are estimated to have the potential to achieve ≥45% overall energy savings for small commercial buildings with similar building load profiles (e.g., relatively large DHW loads coincident with space heating and cooling loads). They could also reduce peak electric demand by 40% or more compared to the all-electric baseline system, depending on how coincident the peak air-conditioning and DHW loads are, enabling reduced electric demand charges. Reduced electricity consumption would also have other benefits, such as lower $NO_x$ and $CO_2$ emissions, and reduced water consumption.

Energy savings are achieved primarily by 1) use of the ground vs. outdoor air as the energy source/sink, 2) very efficient hot water production, and 3) its capacity modulation capability for space heating (SH), space cooling (SC) and WH. During most of the year and particularly during the peak HVAC load months the ground temperature is more favorable for heat pump operation than the outdoor air resulting in higher efficiency operation for the system. The system can meet DHW loads on demand year-round at heat pump COPs (2.5-3.0 or more), much higher than the maximum overall COP of ~0.9-0.95 that standard electric storage WHs can achieve. When space cooling and DHW demands coincide the GS-IHP system can meet both simultaneously at even higher COPs (5.0 or more). Compared to the single-speed electric RTU baseline, the VS capability of the GS-IHP system allows it to meet off-peak space conditioning (and DHW) demands at much increased efficiency and much reduced electric kW demand. Peak electricity demand is reduced by the same mechanisms.

Even with all these benefits, adoption has been limited due to (1) awareness of the technology which was only recently commercialized (2012) and (2) uncertainty about the relative costs and benefits. This project has attempted to address these challenges by (1) quantifying the environmental and energy impacts and costs of the GS-IHP compared to a conventional electric RTU/heat pump and WH; and (2) disseminating this information through DOE Commercial Building Integration (CBI) strategic deployment. By providing funds for this field demonstration, DOE aids in increasing awareness of the energy savings benefits of GS-IHP technology to building owners.

A site selection evaluation was performed to identify suitable commercial building applications based on the HVAC and DHW load requirements. Based on the evaluation, CM in collaboration with ORNL selected two sites. The first was a commercial kitchen attached to a day care facility located in a large church building in Knoxville, TN (mixed-humid climate zone). The second is a homeless shelter dormitory type building (~8,000 $ft^2$ total area) in Oklahoma City, OK (warm-humid climate zone). CM installed GS-IHP systems at both sites. At the Knoxville site the GS-IHP provided HVAC and DHW services for a 463 $ft^2$ commercial kitchen and an adjoining 60 $ft^2$ pantry. The occupancy schedule is from 8:00 am to 5:00 pm Monday through Friday. The Oklahoma installation includes two GS-IHP systems each providing HVAC/WH to 10 residential units (total of ~2500 $ft^2$ each). Two other (non IHP) ground source heat pumps provide HVAC for common areas of the building. All four heat pump systems are connected to a common GHX loop. In addition the two IHP system HW tanks were connected to a common building HW distribution that included a recirculating loop (to minimize wait time for HW at the individual residential unit fixtures). Only one of the GS-IHPs was instrumented for detailed monitoring. The residential areas of the building are occupied 24/7.

A data acquisition (DAQ) system was designed and installed at both sites. Due to construction delays at the Oklahoma site, DAQ installation there was delayed until January 2016. The DAQ system at the Knoxville site has been collecting data continuously since August 18, 2015. Partial data collection began at the Oklahoma City site on January 31, 2016 enabling evaluation of the SH performance from that date through April 2016. However, the flowmeter necessary for detailed measurement of the water heating performance was lost during initial DAQ installation and it was April before a replacement could be procured and installed. Full data collection has been underway in Oklahoma City since May, 2016 enabling evaluation of the WH and SC performance for a multi-family type application.

For the 2015/2016 test year, the Knoxville site GS-IHP provided 54.6% total source energy savings compared to a baseline electric RTU/heat pump and electric WH. Peak demand savings ranged from 54% to 78% per month. Energy cost savings of ~64 % were achieved, with about 65% due to lower demand charges. Carbon emission savings of ~2.45 metric tons were achieved as well. If trading for carbon credits ever becomes a reality, additional cost savings would be realized. These savings significantly exceeded the project technical performance goal of ≥45% energy and carbon emission reductions. For this site, no SH loads were experienced; only SC and WH operation was required for the entire test year.

For the Oklahoma City site delays in completing installation of the DAQ system prevented collection of a full year of performance data. However enough data was obtained to allow a reasonable estimate of SH, SC, and WH energy savings and efficiency vs. the baseline system.

- SH: total energy savings of ~753 kWh (~52%) and average COP of ~4.9 (61.7 days data)
- SC: total energy savings of ~18475 kWh (~50%) and average COP of ~6.9 (117.6 days data)
- WH: total energy savings of ~2293 kWh (~78%) and average COP of ~4.4 (109.6 days data)

Over the actual monitoring period, the GS-IHP at the site demonstrated total site electricity savings of ~4890 kWh (~60%) and carbon emission savings of ~3.47 metric tons, greatly exceeding the project technical goal. Assuming that the daily average loads and COPs above are the same for the balance of the year for each mode it is estimated that total annual energy savings would be ~12,460 kWh with carbon emission savings of ~8.6 metric tons. Note that these numbers can be assumed to be double (~24,900 kWh and ~17.2 metric tons) since the shelter building had two GS-IHP units (the second unit was not monitored). The WH savings indicated were estimated assuming that the tank and line heat losses at Oklahoma City were the same as those measured at the Knoxville site due to problems experienced with the building side water flow instrumentation at the homeless shelter. The assumption is considered to be conservative because the HW loads at the homeless shelter were larger and more continuous than those at the daycare center kitchen in Knoxville; this would tend to make the tank and connecting line standby losses at the Oklahoma City site a smaller fraction of the total WH delivered by the IHP.

If deployed widely, GS-IHPs would significantly decrease energy consumption, energy costs, and emissions related to space conditioning and water heating for small commercial buildings and individual commercial building spaces having a good balance between total DHW loads and HVAC loads. Opportunities for deployment include new construction as well as replacements for failing equipment. Applied nationally to all appropriate commercial building spaces, GS-IHPs could save 0.084 quads of source energy vs. a 13 SEER RTU/heat pump and electric WH baseline.

This field study successfully demonstrated the energy savings, environmental savings, and operational benefits of the GS-IHP technology for small commercial building applications. The two demonstration systems significantly exceeded the project technical objectives of >45% energy and carbon emission savings (>50% at both sites). Best applications of the GS-IHP system are buildings or specific small zones of buildings that have high hot water loads coincident with high space cooling loads. These particular demonstration sites allowed the GS-IHP to take advantage of its combined SC+WH mode featuring fairly extensive recovery of the normally wasted system condenser heat for water heating.

The actual utility bill savings for a building owner will depend on a number of factors, most notably the building's particular load profile, climate region and regional utility rates. Payback analyses were conducted for the Knoxville site system based on the annual energy savings demonstrated. The specific site conditions (limited area, local regulations, etc.) caused drilling costs to be about 3 times higher than typical for the area. For the actual GHX cost, simple payback vs. the baseline RTU/HP/electric WH system was >30 years. With more typical GHX costs for the area the payback would be approximately 13 years. For a "mature market" cost assumption based on experience in Oklahoma for a large number of installations the payback drops to ~8 years, still likely higher than acceptable for most commercial building owners. Assuming an alternative GHX financing option where the local utility (or other entity) installed and owned the GHX loop (e.g., under an energy savings performance contract or other arrangement, etc.) and amortized the cost via a surcharge on the electric bill were available, payback could be reduced to <1 year.

The economics of GS-IHPs will vary from site to site for several reasons, including:

- Regional differences in drilling costs, local site conditions and requirements, and financing options can cause the GHX loop installation costs to vary over a wide range even within a given region. Where local site conditions are unfavorable (restricted area, local permitting/regulation restrictions, etc. as experienced at the Knoxville site) GHX installation costs can be prohibitive

- Local electricity rate structures may limit the operating cost savings achievable, leading to higher payback periods.

Increasing the adoption of high-efficiency integrated HVAC/WH systems like the GS-IHP will require a change in the way HVAC contractors, design engineers, and building owners and operators consider them due to their increased installation cost. Raising awareness of the availability and the potential lifetime energy savings of GS-IHPs may encourage more industry professionals to evaluate them for their buildings, and determine whether the systems offer an acceptable payback based on climate, operations, building design, etc. Additionally, system designers have difficulty using popular building modeling tools to evaluate nonconventional equipment.

The following actions are recommended for promoting adoption of GS-IHP technology, including:

For Developers of Building Energy Modeling Tools:

- Design specific equipment modules for GS-IHP and include as an option within the modeling software

For DOE and Other Efficiency Organizations:

- Facilitate quick energy savings calculations by developing a simple set of regional climate maps estimating equipment runtimes for different scenarios

- Develop best practice guides based on evaluations against different baseline equipment and building types.

For Electric Utilities:

- Educate commercial customers on the life-cycle cost of GS-IHP technologies and include them in available grant, incentive, or financing programs.

For Local/State Government Agencies, Electric Utilities, other Efficiency Organizations:

- Consider promoting and/or establishing specific financing options for GHX loops for commercial customers

- Consider promoting and/or establishing incentives for GS-IHP systems for commercial customers

# II. Introduction

## A. Problem Statement

Reducing energy consumption in buildings is key to reducing or limiting the negative environmental impacts from the building sector. According to the United States (U.S.) Energy Information Administration (EIA), in 2012, commercial buildings consumed 18.1 quads of primary energy, which was 18.6% of the total U.S. primary energy consumption.[1] The primary energy consumption in the commercial sector is projected to increase by 2.8 quads from 2013 to 2040, the second largest increase after the industrial sector.[2] Further space heating, space cooling, and ventilation (HVAC) services accounted for 31% of the energy consumption in commercial buildings.[3] Small commercial buildings (≤10,000 $ft^2$ floor space) represent about 21% of the commercial floor space in the United States.[4] Many such buildings (and defined spaces within larger commercial and institutional buildings) also have significant domestic hot water (DHW) loads, such as restaurants, laundry facilities, health & fitness centers, etc. The all-electric subset of small commercial buildings consumes approximately 0.160 Quads of primary electricity energy annually for HVAC and WH services.[5]

More than half of U.S. commercial building space is cooled by packaged HVAC equipment, most of which are rooftop units with less than 50 tons of cooling capacity.[6] Existing rooftop HVAC units consume more than 1.3% of total U.S. energy annually. Rooftop units are popular because they are inexpensive, provide zonal control, are easy to install, and can be serviced without disrupting occupants. Given their advantages, their large market share will likely continue.

Today's RTUs are inefficient for a host of reasons. Many are oversized to handle peak ambient temperatures. Undersized/dirty evaporator coils reduce compressor efficiency. Capacity is also wasted by over-drying indoor air in dry climates. Single-speed blowers run for ventilation during all occupied

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[1] U.S. Energy Information Administration, Annual Energy Outlook 2015, available online at http://www.eia.gov/forecasts/aeo

[2] U.S. Energy Information Administration, Annual Energy Outlook 2015, available online at http://www.eia.gov/forecasts/aeo

[3] U.S. Energy Information Administration, Annual Energy Outlook 2015, available online at http://www.eia.gov/forecasts/aeo

[4] EIA, CBECS 2003 Table C1, the percent commercial floor space in buildings ≤10,000 $ft^2$ (total floor space in buildings ≤10,000 $ft^2$ / total building floor space), http://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set9/2003html/c1.html

[5] EIA, CBECS 2003 Table E3, electricity consumption by end use for non-mall buildings, http://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set19/2003html/e03.html

[6] EIA (US Energy Information Administration), 2015. 2012 Commercial Buildings Energy Consumption Survey (CBECS), Tables B1 and B2. http://www.eia.gov/consumption/commercial/data/2012/#summary (accessed September 2015).

hours, using about half of annual rooftop unit energy. Improving their operational efficiency is essential for enhancing overall commercial building energy performance.

Conventional storage WHs particularly electric WHs are approaching thermodynamic limits to their efficiency potential. Storage WHs of the type used in small commercial buildings are subject to DOE minimum efficiency requirements. For instance, a 50 gallon electric WH must have an energy factor (EF, an annual efficiency metric) of ≥0.94. Significant increases in WH efficiency will need to come from use of heat pumping technologies; either combined or integrated heat pumps (IHP) or standalone heat pump water heaters (HPWH).

ClimateMaster, Inc. (CM) and Oak Ridge National Laboratory (ORNL) jointly developed a new, highly efficient electric integrated HVAC and water heating (WH) system – the ground-source integrated heat pump (GS-IHP). The new GS-IHP system is a combination of a very highly efficient variable-speed (VS) water-source heat pump (WSHP) capable of space heating and cooling and domestic water heating coupled to a geothermal energy source/sink. Most often the geothermal source/sink is a closed-loop ground heat exchanger (GHX loop).

The WSHP unit was tested at Air-conditioning, Heating, and Refrigeration Institute (AHRI) ground loop heat pump (GLHP) conditions[7] and achieved the highest rated efficiencies of any commercially available WSHP unit at the time of its initial commercial launch in 2012 - heating coefficients of performance (COP) of 5.1 and 3.3 at minimum and maximum speeds, respectively, and cooling energy efficiency ratios (EER) of 45.1 and 21.6 at min and max speeds for the nominal 4-5 ton capacity units used at the two field sites described in this report.[8] CM also produces a smaller, 2-2.5 ton nominal capacity unit with slightly higher efficiencies at maximum compressor speeds – 3.6 COP and 24.3 EER. Because tests at fixed conditions do not represent the “true” seasonal energy efficiency, field tests and demonstrations are needed to show the potential savings potential of the GS-IHP. Field demonstrations provide performance comparisons in “real” conditions and allow for: 1) comparison of annual energy savings of the GS-IHP to a standard efficiency electric rooftop unit heat pump (RTU/heat pump) and electric WH; 2) identification of non- performance related issues, such as maintenance requirements; and 3) capturing lessons learned and how-to guidance in a concise case study for market deployment.

## B. Opportunity

The GS-IHP system was developed primarily for residential buildings and is expected to reduce space heating/cooling energy use by ≥50% and WH energy use by ≥75% for that application compared to

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[7] Air-conditioning, Heating, and Refrigeration Institute, ANSI/AHRI/ASHRAE/ISO Standard 13256-1, “*Water-to-Air and Brine-to-Air Heat Pumps — Testing and Rating for Performance,*” 1998.

[8] ClimateMaster catalog for Trilogy Q-mode (QE) series water source heat pump products, September 2014.

minimum efficiency electric heat pump and WH systems.[9] GS-IHPs are estimated to have the potential to achieve ≥45% overall energy savings for small commercial buildings or special purpose spaces within larger buildings with similar building load profiles (restaurants, commercial/institutional building kitchen facilities, hotel/motel/dormitory type buildings, laundry facilities, health/fitness centers, etc.). They could also reduce peak electric demand by 40% or more compared to the baseline electric system, depending on how coincident the peak air-conditioning and WH loads are, enabling reduced electric demand charges. Reduced electricity consumption would also have other benefits for power plants, such as lower $NO_x$ and $CO_2$ emissions and reduced cooling water consumption. Even with all these benefits however, adoption has been limited due to (1) awareness of the technology which was only recently commercialized (2012) and (2) uncertainty about the relative costs and benefits. This project attempts to address these challenges by (1) quantifying the energy savings and costs of the GS-IHP compared to the minimum efficiency electric baseline system; (2) disseminating this information through strategic deployment channels, and (3) encouraging adoption of GS-IHPs that provide greater energy savings so that building owners, managers and developers can make more informed choices.

Energy savings are achieved primarily by very efficient hot water production and its capacity modulation capability for space conditioning and WH. The system can meet WH loads on demand year-round at heat pump COPs (2.5-3.0 or more), much higher than the maximum overall COP of ~0.9-0.95 that standard electric storage WHs can achieve. Additionally, coincident WH and space cooling demands can be met simultaneously at even higher COPs (5.0 or more). Compared to the single-speed electric RTU baseline, the VS capability of the GS-IHP system allows it to meet part-load space conditioning (and WH) demands at much increased efficiency and much reduced electric kW demand. Peak electricity demand is reduced by the same mechanisms.

## C. Technical Objectives

The technical objective of this project is to demonstrate the capability of the new GS-IHP system to reduce overall energy use for space heating, space cooling, and water heating by at least 45% vs. a conventional electric RTU and electric WH in a light commercial building application. This project supports the DOE-Building Technologies Office (BTO) goals of reducing HVAC energy use by 20% and water heating by 60% by 2030.

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[9] *Ground-Source Integrated Heat Pump (GS-IHP) Development*, CRADA Final Report, CRADE NFE-07-0100, Oak Ridge National Laboratory, ORNL/TM-2013/194, May 2013.

## D. Technology Description

The demonstrated GS-IHP system is comprised of a nominal 4-5 ton (cooling) WSHP packaged unit coupled to an external geothermal source/sink system and a domestic hot water (DHW) storage tank. For the demonstration systems in this study the geothermal system was a closed-loop ground heat exchanger (GHX loop). Other geothermal source/sink systems are possible as well – e.g., closed-loop heat exchanger submerged in a pond, lake, or river; etc. The WSHP package was CM's Trilogy 45® Qmode® IHP product (http://www.climatemaster.com/residential/geothermal-heat-pumps-2/trilogy/ and http://www.climatemaster.com/residential/trilogy/qe/). Table 1 summarizes the Trilogy/GS-IHP system rated/design performance compared to that of a conventional electric RTU/heat pump with a conventional electric storage water heater (WH).

The Trilogy WSHP features a variable-speed (VS) compressor along with a VS blower for indoor air circulation and VS pumps for GHX loop and DHW loop circulation. The system provides variable space cooling, space heating, and water heating capacity as needed by modulating over set point temperature ranges. Four different operating modes are available as listed below:

- Space cooling, or SC (factory set at 1½ to 4 tons for 4-ton size unit; installer adjustable to maximum 5 ton capacity)
- Space heating, or SH (1½ to 5 tons for 4-ton size unit)
- Combined WH plus space cooling, or SC+WH
- Dedicated water heating year-round, or DWH

In addition, the VS compressor and blower allow the unit to increase/decrease dehumidification (moisture removal) capacity as needed in response to space RH level when in SC modes to maintain comfort levels in the conditioned without sacrificing efficiency. Similarly the air delivery temperature can be adjusted as needed in SH mode. Compact HX designs are used for the air/refrigerant space heating/cooling coil and the GHX loop/refrigerant and hot water/refrigerant coils. This reduces the required system refrigerant charge and associated environmental risks.

The Trilogy systems include a "smart" hot water tank (HW) which includes electric elements for back-up or emergency water heating and HW fittings to minimize mixing of tank water during heat pump WH operation in order to maintain tank stratification. This helps ensure that the hottest water stays at the top of the tank and ready for use by the occupants. Tank controls are integrated with the heat pump unit controls.[10]

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[10] ClimateMaster, Inc. product brochure, "Trilogy® 45 Geothermal Systems," March 2015.

### Table 1. Summary of GS-IHP versus conventional RTU + Electric Storage WH

| | Base (electric RTU/heat pump & WH) | GS-IHP |
|---|---|---|
| Compressor/number | Scroll/1-speed | Scroll/variable speed |
| Refrigerant type | R410A | R410A |
| Design Cooling rating | 48,000 Btu/hr at 95°F outdoor temp[a] | 18,000 Btu/hr @ min speed[b]<br>48,000 Btu/hr @ max speed[b] |
| Design Heating rating | 45,000 Btu/hr at 47°F outdoor temp[a]<br>28,000 Btu/hr at 17°F outdoor temp[a] | 24,000 Btu/hr @ min speed[b]<br>60,000 Btu/hr @ max speed[b] |
| Design water heating capacity; dedicated WH | 4.5 kW (conventional electric WH) | ~28,000 Btu/hr, low speed<br>~40,000 Btu/h, high speed<br>(110°F entering HW temp.; 35-80°F entering water temperature from GHX loop)[c] |
| Design cooling plus WH capacity; combined mode | na | 18,000 Btu/hr cooling + 24,000 Btu/hr WH, low speed<br>48,000 Btu/hr cooling + 69,000 Btu/hr WH, high speed<br>(110°F entering HW temperature)[c] |
| Rated cooling efficiency | 11.4 EER at 95°F outdoor temp.<br>13.0 SEER[a] | 45.1 EER @ min speed[b]<br>21.6 EER @ max speed[b] |
| Rated heating efficiency | 3.05 COP at 47°F outdoor temperature[a]<br>2.26 COP at 17°F outdoor temperature[a] | 5.1 COP @ min speed[b]<br>3.3 COP @ max speed[b] |
| Design water heating efficiency; dedicated WH | 1.0 COP (conventional electric WH) | 2.5-5.0 COP<br>(110°F entering HW temp.; 35-80°F entering water temperature from GHX loop)[c] |
| Design cooling plus WH efficiency; combined mode | na | Up to 30 EER combined, low speed<br>Up to 19 EER combined, high speed<br>(110°F entering HW temp.)[c] |
| Unit dimension (in) | 45 L X 47 H X 76 W | 25.4 L X 56 H X 30.6 W |
| Unit weight | 590 lb, RTU | 448 lb, Trilogy WSHP |
| Electrical | 13.0 kW, RTU<br>4.5 kW, WH tank | 8.5 kW, heat pump unit<br>4.5 kW, WH tank |

[a] Certified per ANSI/AHRI Standard 210/240

[b] Certified per ANSI/AHRI/ISO/ASHRAE Standard 13256-1. The Trilogy can be adjusted at installation to 5-ton maximum cooling capacity as was done at the Oklahoma City site; a 5-ton cooling capacity conventional RTU heat pump was used for the baseline comparisons at that site as noted in later sections of this report.

[c] ClimateMaster product catalog [September, 2014]

# III. Project Scope

A new technology (GS-IHP) based on a DOE funded concept development is estimated to reduce both site and source energy consumption for HVAC and water heating (WH) by at least 45% overall compared to minimum efficiency electric HVAC/WH systems. This would also have other benefits, such as reduced electrical demand and lower $NO_X$ and $CO_2$ emissions associated with the lower electricity consumption. Even with all these benefits, adoption has been limited due to (1) awareness of the technology which was only recently commercialized (2012) and (2) uncertainty about the relative costs and benefits. This project attempts to address these challenges by (1) quantifying the environmental and energy impacts and costs of the GS-IHP compared to a conventional electric RTU and electric WH; (2) disseminating this information through CBI strategic deployment, and (3) encouraging adoption of the technology so that building owners, managers and developers can make more informed choices.

This report is not intended to be used as a recommendation for using a GS-IHP based purely on the current results; rather this report emphasizes the potential savings opportunities when favorable conditions exist. When selecting HVAC equipment for particular applications, additional considerations of applicability, installation methods, electricity and gas costs, necessity for water heating, etc., are needed.

# IV. Project Approach

## A. Field Site Selection and Installation

A site selection evaluation was performed to identify suitable commercial building applications based on the HVAC and water heating load requirements. Based on the evaluation, CM in collaboration with ORNL selected two sites. The first was a commercial kitchen attached to a day care facility located in a large church building in Knoxville, TN. Knoxville is located in climate Zone 4A (Mixed-Humid per Figure 1 and Table 2 below). The second is a homeless shelter dormitory type building (~8,000 $ft^2$ total floor space) in Oklahoma City, OK – climate Zone 3A (Warm-Humid). CM and its subcontractors (City Heat & Air of Knoxville and Comfortworks, Inc. of Goldsby, OK) designed and installed GS-IHP systems at both sites based on their Trilogy 45 IHP Qmode product. Figures 2-10 provide photos and GHX schematics for the two installations. At the Knoxville site (Figures 2-6) a single GS-IHP provided HVAC and DHW services for the 463 $ft^2$ kitchen and adjoining 60 $ft^2$ pantry. The occupancy schedule is 8:00 am to 5:00 pm Monday through Friday except for holidays.

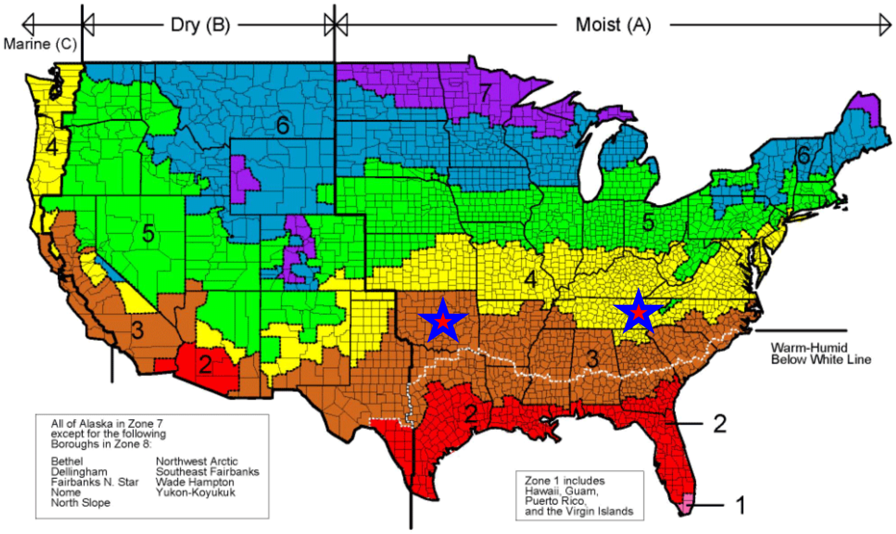


**Figure 1. Map of USA climate zones (Source: ANSI/ASHRAE/IESNA Standard 90.1-2007). Stars indicate GS-IHP demonstration site locations**

**Table 2. Description of USA climate zones (Source: ANSI/ASHRAE/IESNA Standard 90.1-2007)**

| Zone Number | Name | Thermal Criteria |
|---|---|---|
| 1 | Very Hot – Humid (1A),<br>Dry (1B) | 5000 < CDD10°C |
| 2 | Hot – Humid (2A), Dry (2B) | 3500 < CDD10°C ≤ 5000 |
| 3A and 3B | Warm – Humid (3A), Dry (3B) | 2500 < CDD10°C ≤ 3500 |
| 3C | Warm – Marine | CDD10°C 2500 AND*<br>HDD18°C 2000 |
| 4A and 4B | Mixed – Humid (4A), Dry (4B) | CDD10°C ≤ 2500 AND<br>2000 < HDD18°C ≤ 3000 |
| 4C | Mixed – Marine | 2000 < HDD18°C ≤ 3000 |
| 5A, 5B and 5C | Cool– Humid (5A), Dry (5B), Marine (5C) | 3000 < HDD18°C ≤ 4000 |
| 6A and 6B | Cold – Humid (6A), Dry (6B) | 4000 < HDD18°C ≤ 5000 |
| 7 | Very Cold | 5000 < HDD18°C ≤ 7000 |
| 8 | Subarctic | 7000 < HDD18 °C |

*CDD (cooling degree C-days) ≤2500 AND HDD (heating degree-C days) ≤2000

Figure 2. Aerial view of the Knoxville, TN test site (Photo source: Google Maps)

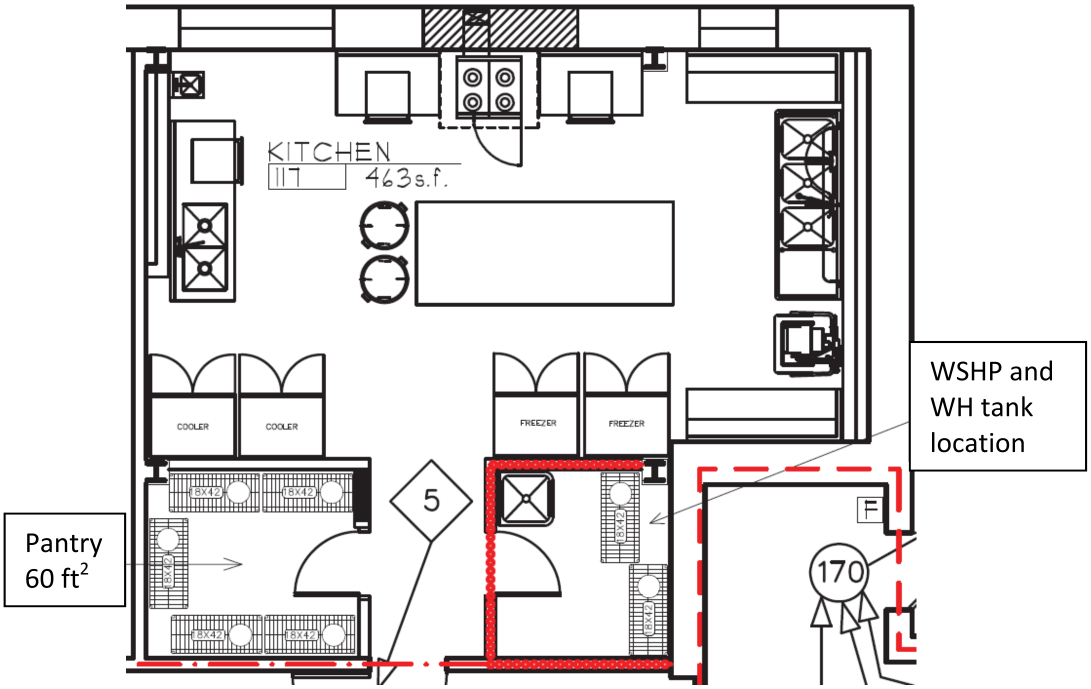


Figure 3. Kitchen floor plan, Knoxville, TN test site

Figure 4. Trilogy WSHP system as installed at the Knoxville, TN test site

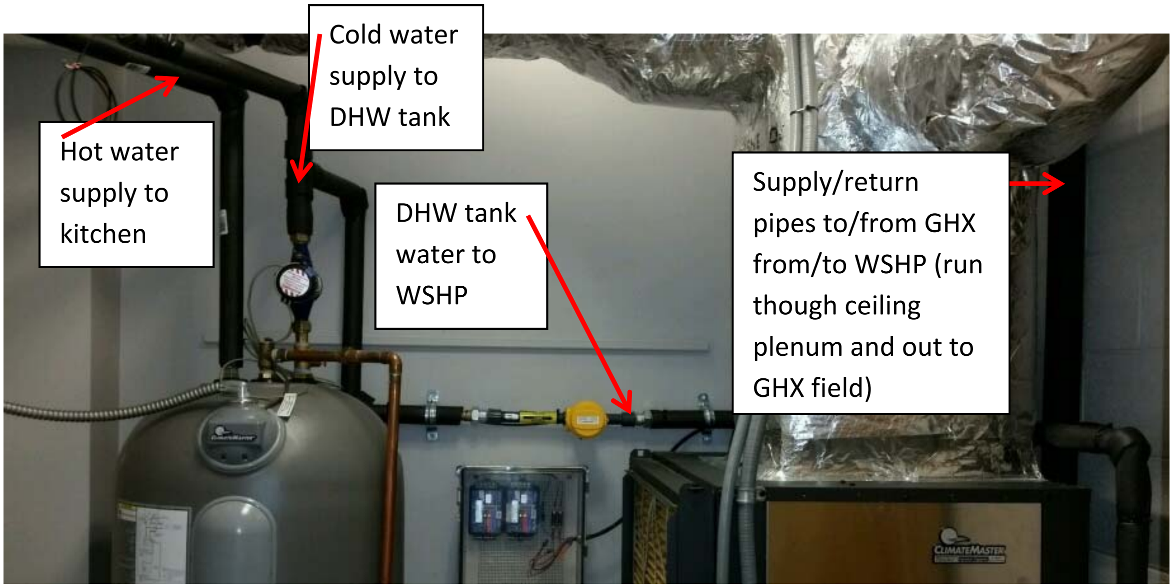


Figure 5. WH piping connections and flowmeters at Knoxville site.

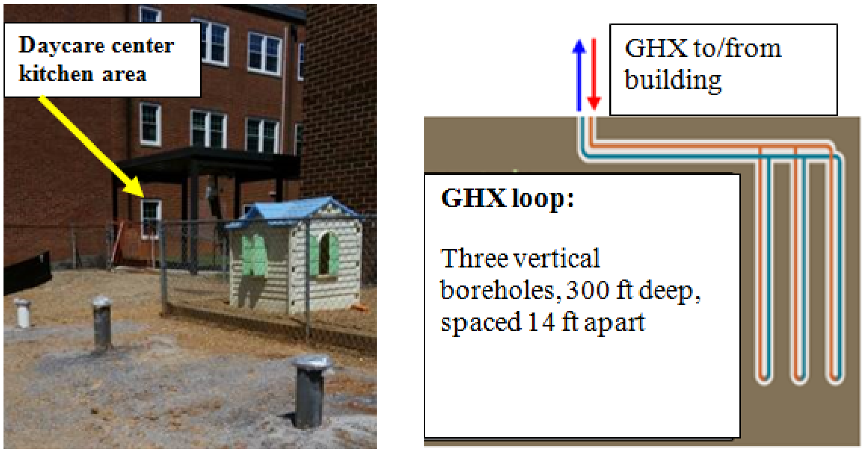


**Figure 6. GHX loop location and schematic for Knoxville, TN test site (graphic source: ClimateMaster)**

The Oklahoma installation (Figures 7-10) includes two Trilogy-based GS-IHP systems with 105 gallon hot water (HW) tanks each providing HVAC/WH to 10 residential units (total of ~2500 ft$^2$ each). Due to the higher peak design cooling loads at this site the Trilogy units were set up during installation to provide maximum cooling capacity of 5 tons (60,000 Btu/h) each. Two other (non IHP) ground source heat pumps provide HVAC for common areas of the building. The total nominal cooling capacity for all four heat pump systems was 18 tons (216,000 Btu/h) and all are connected to a common GHX loop. Each WSHP unit used its own internal loop circulator pump; no central system pump was used. Only one of the GS-IHPs was instrumented and monitored in detail. The residential areas of the building are occupied 24/7.

The two Trilogy HW tanks are connected to a common building HW distribution system. This system includes a HW recirculation loop to minimize the wait time for HW at the fixtures in each residential unit; the recirculation pump energy use was not monitored. Only one of the tanks was instrumented to attempt to determine the HW energy delivered to the building HW distribution system.

**Figure 7. Oklahoma City, OK test site host building**

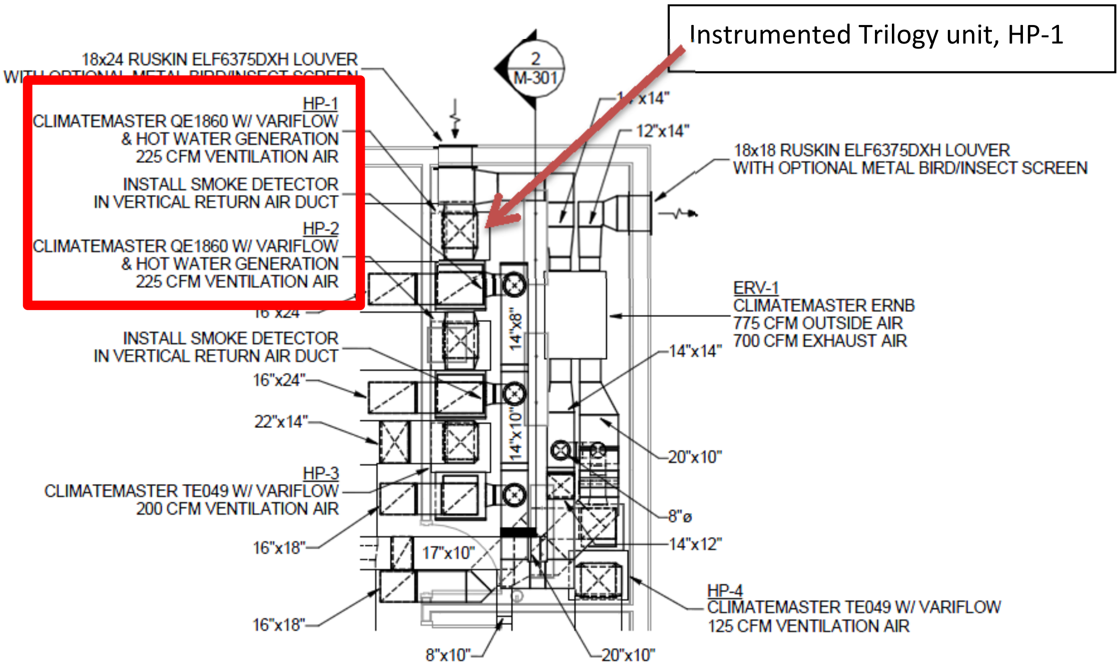
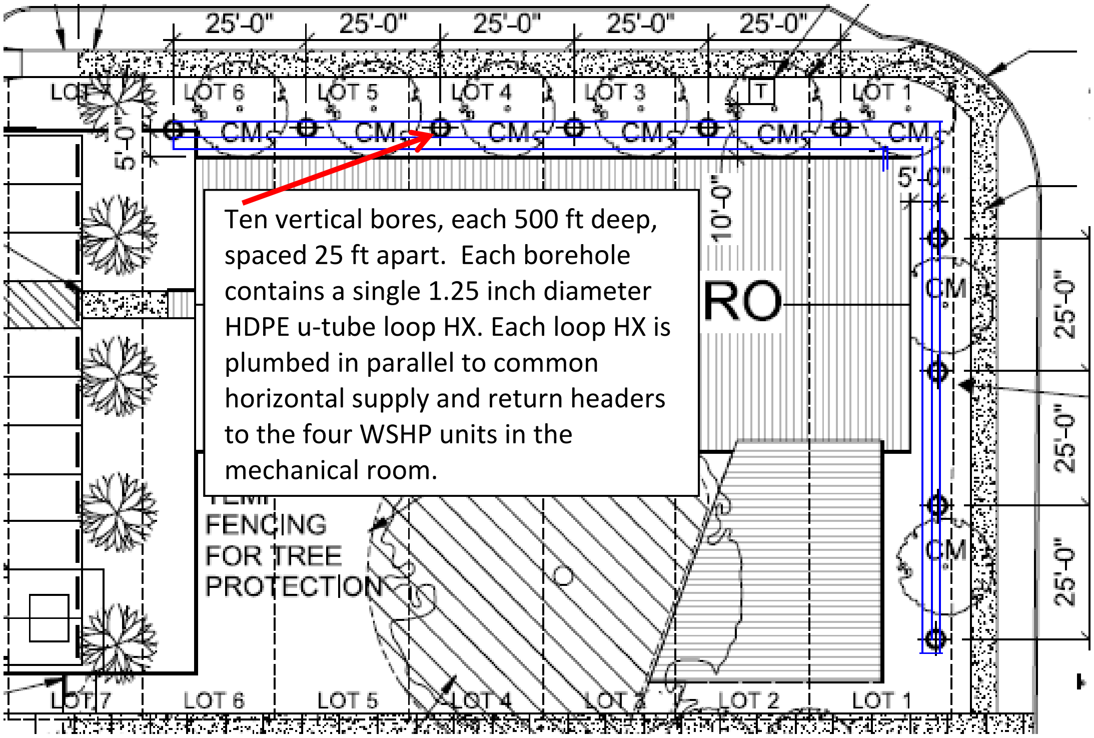


**Figure 8. Oklahoma City, OK building mechanical room floor plan; Trilogy units are HP-1 and HP-2 (Source: ClimateMaster)**

**Figure 9. Oklahoma City host building mechanical room; instrumented Trilogy is on lh side against back wall; Trilogy HW tanks at right (Source: ClimateMaster)**



Ten vertical bores, each 500 ft deep, spaced 25 ft apart. Each borehole contains a single 1.25 inch diameter HDPE u-tube loop HX. Each loop HX is plumbed in parallel to common horizontal supply and return headers to the four WSHP units in the mechanical room.

**Figure 10. GHX loop location and details for Oklahoma City, OK test site (Source: ClimateMaster)**

There were strong advocates at both sites to serve as the primary points of contact with access to the space, equipment, and operations. The areas or spaces being considered for demonstration are representative of the conditions and functions for the expected application of the technology.

## B. Metering and Monitoring Plan

The test systems were installed and commissioned to ensure proper operation at both sites. Data acquisition (DAQ) systems were designed and installed at each site. The DAQ system at the Knoxville site began collecting data continuously on August 18, 2015 until the end of the test period with only one ~3-day outage. Due to construction delays at the Oklahoma site DAQ installation there was delayed. Partial data monitoring (for SH performance) began there on January 31, 2016. A water flow meter required for monitoring of WH operation was lost during initial DAQ installation and could not be replaced and installed until mid-April. Full data collection, including WH mode operation, has been underway at Oklahoma City since May 19, 2016, but with several outages as noted in Section VI.

Data is collected at 15 second intervals, averaged into one minute intervals, and sent to a remote server at ORNL via the internet. An error analysis of the instrumentation (Table 3) was included to determine the overall sensor accuracy of the data collection. During the collection of data, the GS-IHPs were operated as normal with a wall thermostat to control space heating and cooling operation, and a WH tank thermostat to control WH operation.

ORNL pulled the data files from the test sites and stored them on file storage resources at ORNL. The data was subsequently loaded into a searchable database. This facilitates access to the data since it can be queried on any number of constraints (i.e., date ranges, parameter values, etc.) by most data analysis packages. MATLAB and Excel were used to analyze the data for this report.

**Table 3. Instrumentation**

| Monitoring point | Manufacturer | Model No. | Error |
|---|---|---|---|
| Trilogy WSHP unit & WH tank element energy consumption | Continental Control Systems | WattNode models WNC-3Y-208-MB and WNB-3Y-208-P, respectively | ±0.5% W reading for 5-100% rated current (±1% of reading for 1-5% rated current) |
| Line voltage | Continental Control Systems | WattNode model WNC-3Y-208-MB | ±0.5% V reading |
| Supply/Return Temperatures, Trilogy to/from GHX loop | Omega | PM-1/10-1/8-6-1/8-P-3; platinum resistance temperature device (RTD), immersion | ±(0.03 + 0.0005 \|t\| )°C From 0 to 100°C[a] |
| Supply/discharge Temperatures, Trilogy to/from DHW tank | Omega | PM-1/10-1/8-6-1/8-P-3; platinum RTD, immersion | ±(0.03 + 0.0005t)°C From 0 to 100°C[a] |
| Supply/Return Temperatures, DHW tank to/from building HW distribution network | Omega | PM-1/10-1/8-6-1/8-P-3; platinum RTD, immersion type | ±(0.03 + 0.0005t)°C From 0 to 100°C[a] |
| Flow; GHX loop | Omega | FMG3001-PP | ±0.8%, max[b] (~1-20 gpm) |
| Flow, DHW tank loop | Omega | FMG3001-PP | ±0.8%, max[b] (~1-10 gpm) |
| Flow, building water supply to DHW tank | Omega | FTB8007B-PT | ±1.5% (0.22-22 gpm) |
| ID space temperature | Trilogy onboard sensor | Thermistor included with CM thermostat | ±0.56 °C (±1.0°F) |
| ID space RH (%) | Trilogy onboard sensor | Johnson Controls model HT-6703 | ±3 %RH |
| WH upper tank wall temperature | Trilogy onboard sensor | Thermistor mounted to WH tank wall | ±0.56 °C (±1.0°F) |
| Temperature in/out Trilogy air coil | Omega | Type T TC | 0.75% Full Scale |
| RH% in/out Trilogy air coil | Omega | HX92AC-D | ±2.5% RH from 20 to 80% RH; ±3.1% RH below 20 and above 80% RH @ 22°C with temp coefficient of ±0.1% RH/°F Output |
| Ambient Temp | Local airport weather data | Ecobee web site accessed via Trilogy control system | Na |

[a] All RTDs underwent 5 point calibration over expected temperature operating range (30 to 140 °F) against NIST traceable thermometer; linear fit to temperature standard with $R^2$ of 1.000.

[b] Results of factory calibration against NIST traceable standard over expected operating flow ranges.

Figure 11 shows a schematic of the GS-IHP system, including the critical sensor locations.

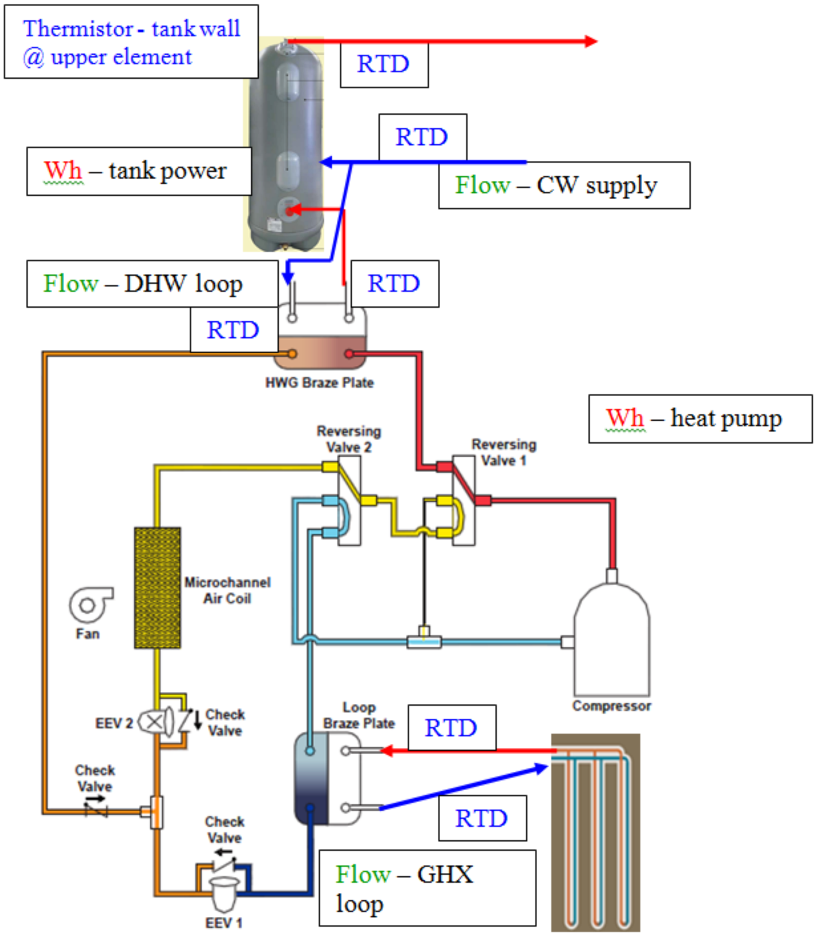


**Figure 11. GS-IHP schematic with critical sensor locations (Graphic source: ClimateMaster)**

## C. Energy Savings Estimation Approach

The goal of this demonstration is to estimate the annual energy savings and costs of the GS-IHP technology versus a standard efficiency electric RTU and electric water heater.

The site measured data (loop temperatures and flow rates) are post-processed and used to compute space heating, space cooling, and water heating energy delivered by the GS-IHP for each mode using the equations below. These calculated values are stored along with the measured data for each 15-second data scan.

Space cooling delivered (SC Mode)

$$Q_{SC} = V_{GroundLoop}\rho_{GroundLoop}c_{GroundLoop}(LWT - EWT) - W_{IHP}$$

Space cooling delivered (SC+WH Mode)

$$Q_{SC} = Q_{WH,IHP} - W_{IHP}$$

Space heating delivered (SH mode)

$$Q_{SH} = V_{GroundLoop}\rho_{GroundLoop}c_{GroundLoop}(EWT - LWT) + W_{IHP}$$

Water heating delivered by IHP to the WH tank and connecting lines between tank and IHP (DWH mode)

$$Q_{WH,IHP} = V_{DHWLoop}\rho_{DWHLoop}c_{DWHLoop}(LDWHT - EDWHT)$$

Water heating delivered to building

$$Q_{WH} = V_{Hot}\rho_{Hot}c_{Hot}(T_{Hot} \quad - T_{Cold})$$

(Note 1: $T_{Hot}$ was taken to be the maximum of a) the leaving hot water temperature measured by an immersion RTD sensor in the hot water exit line to the building distribution system, or b) the upper tank wall temperature measured by a thermistor located near the upper element. Many of the hot water draws experienced were of such small volumes and short durations that the response time of the RTD was too slow to capture an accurate measure of the leaving hot water temperature.)

(Note 2: In addition it was discovered late in the project that the flowmeter at the Fountain City site providing the $V_{Hot}$ measurement was subject to some flow oscillations in the cold water line. Due to the nature of the meter, these oscillations caused the flow measurement to be higher than the actual flow. This erroneous flow was filtered out of the data by checking the corresponding temperature of the hot water leaving the tank. When the measured flow was caused by oscillations, the hot water temperature sensor was far enough away from the tank that it did not increase in temperature. Any flow data without a corresponding increase in hot water temperature or that was comprised of less than 3 pulses from the flow meter was removed from the data set. This may have inadvertently eliminated some small flow events (<0.2 gallons), so the calculation of the water heating energy delivered to the building is likely conservative. At the Oklahoma City site there was significant uncertainty about where to place the sensor owing to the presence of the HW recirculation system and the fact that there were two IHP systems with water tanks. With the amount of instrumentation budgeted for the project it was not possible to obtain a good measure of the WH energy actually delivered to the building HW distribution system from each individual tank with any confidence. Therefore we decided to make the assumption that the tank and connecting line standby heat losses measured at Knoxville (~23% combined) also applied to the Oklahoma City system. This is believed to be a somewhat conservative assumption based on the fact that the IHP in Oklahoma City experienced heavier and more continuous WH loads than did the system in Knoxville. The system in Oklahoma spent an average of ~12% of its total test period hours in WH modes compared to <5% for the Knoxville system. With longer runtimes and heavier WH loads, the HW tank and connecting line standby heat losses should be a smaller fraction of the total load.)

Where –

- $EWT$: GHX loop fluid temperature entering WSHP (RTD)
- $LWT$: GHX loop fluid temperature leaving WSHP (RTD)

- $EDWHT$: domestic hot water temperature entering WSHP (RTD)
- $LDWHT$: domestic hot water temperature leaving WSHP (RTD)
- $T_{Cold}$: cold water supply temperature to WH tank (RTD)
- $T_{Hot}$: hot water temperature leaving WH tank (see parenthetical note above)
- $V$: fluid flow rate
- $\rho$: fluid density
- $c$: fluid specific heat

Energy consumption for the GS-IHP is measured directly by two watt-hr meters, one for the Trilogy unit ($W_{IHP}$) and one for the WH tank back up elements ($W_{tank}$). For the combined space cooling and water heating mode the energy consumption is apportioned to each output proportional to the output capacity by a data analysis program and stored along with the loads data for each time step. This implicitly assumes that the efficiency, or coefficient of performance (COP) for both SC and WH in the combined mode is the same.

The energy delivery and measured energy use for the GS-IHP in each mode are totaled for each month/season and compared with the estimated energy used by the baseline RTU/electric WH to meet the same loads. The baseline RTU performance use was estimated using performance curves that account for variations in outdoor temperature and humidity, indoor temperature and humidity, time/temperature controlled defrosting, cyclic losses, and supplemental resistance heating. Defrost cycles were assumed to be 5.8% of the operating time at outdoor temperatures below 40°F and the defrost tempering heat energy was equal to the cooling done during the defrost cycle. Note that the measured cooling load was not broken down into sensible and latent parts. Since the GS-IHP varies its VS blower speed (rpm) to adjust the split of sensible and latent cooling required by the space, it is assumed that it delivers the minimum total cooling energy required to maintain comfortable indoor conditions. In contrast, the baseline RTU unit does not have a VS indoor blower and therefore cannot adjust the ratio of sensible and latent cooling delivered. This either results in insufficient latent cooling and discomfort or excess latent cooling and wasted energy. As such, assuming similar comfort levels are maintained by both systems, the SC savings calculated for the GS-IHP over the RTU system are conservative. Energy savings and carbon emission reductions for the GS-IHP are computed as the difference in these values vs. the Baseline.

## D. Cost Savings Approach

Electricity rates were obtained from the local electric utilities at each demonstration location and used along with the measured energy use of the GS-IHP and the estimated energy use of the baseline system to determine annual energy related costs. for Knoxville, the rate data include both demand charges and hourly usage charges. For Oklahoma, only hourly usage charges were available for residential buildings like the homeless shelter. Annual energy savings for the GS-IHP at each site are estimated based on the energy costs estimated using these rates. GS-IHP system installed cost estimates (high and low) were made for the Knoxville site design vs. a baseline RTU/HP and electric WH using high and low estimates for GHX loop installation cost.

## E. Installation Cost

Actual system installation cost data were compiled for each site and are listed below. In addition to the actual cost for Knoxville an assumed “mature market” installation cost estimate was made for use in the payback analysis discussed in this report. Payback estimates (high and low) were made for a GS-IHP system of the Knoxville site design vs. the baseline RTU/HP and electric WH using the range of GS-IHP installation cost estimates below.

The major variable impacting GS-IHP system installation cost is the external geothermal heat source/sink. As noted earlier, in most cases this involves drilling/excavation and installation of a GHX loop (usually of the vertical bore field type). For the Knoxville site, three “out of normal” installation issues were experienced that negatively impacted the actual system costs.

- First and most important were the drilling issues related to the urban location. The major complication was that provisions had to be made to recover all the drilling cuttings and fluids or “mud” to avoid overloading the nearby city storm sewers. A vacuum pump truck had to accompany the drill rig to the site to accomplish this recovery causing a significant increase in the drilling costs.
- Secondly, space available for the GHX field at the site was relatively tight so a horizontal boring machine had to be used to run the GHX header pipes from the GHX field to the building. In most cases a much less expensive trenching machine is used to dig a trench for the headers. The space issue also limited the maximum distance between the boreholes to 14 ft instead of CM’s normally recommended 20-25 ft spacing. While this did not directly impact installation cost it could potentially impact long term performance if the annual loads on the loop are significantly unbalanced (e.g. annual heat rejection to the ground is much greater than annual heat extraction).
- Finally, the GHX header piping had to be partly exposed to ambient air. This was because it was not possible to run the headers under the building to the WSHP location next to the kitchen facility due to existing underground infrastructure. The header piping had to be run up the outside wall and then through a ceiling plenum above the WSHP (see Figure 12, below, and Figure 5) and added about a day to the installation time. This situation occurs only rarely in the experience of the installing contractors. It also required that an antifreeze solution be added to the water in the GHX loop in early January 2016 to avoid any potential loop freeze problems. This added an estimated $700 to the system cost (cost of the antifreeze plus an additional site visit) and slightly reduces the system performance relative to a water only loop.

The installing contractor estimated that for a more rural location without all the above complicating factors the GHX install costs could have been reduced by a factor of 2-3.[11]

**Figure 12.** GHX loop headers attached to wall outside kitchen facility, Knoxville site

No “out of normal” GHX installation issues occurred for the Oklahoma City site.

Knoxville site GS-IHP installation cost estimate:

- GHX actual (per installer billing): $38,000 (~$42/bore ft)
- GHX mid (without issues above): $15,000 (~$17/bore ft)[12]
- GHX low (mature market estimate): $9,600[13] (~$10.70/bore ft)
- Trilogy unit: $ 9,800[14][15]
- Indoor installation: $ 1,600[16]
- Totals
    - high: $49,400
    - low: $26,400

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[11] Personal communication, M. Davis (City Heat and AC) to Van Baxter, August 26, 2016.

[12] Compares to average GHX installation costs of $14.94/bore ft in the South and $12.99/bore ft in the Midwest based on a survey of GHSP systems in these regions; as reported by E. C. Battocletti and W. E. Glassley in “Measuring the Costs and Benefits of Nationwide Geothermal Heat Pump Deployment,” prepared for the USDOE Geothermal Technologies Program, February 2013.

[13] Personal communication, D. Ellis (Comfortworks, Inc.) to Van Baxter, August 29, 2016. Estimated mature market GHX installation cost including drilling, u-tube pipe loop insertion, backfill/grouting of boreholes, trenching & header pipe to building, and filling/flushing of GHX pipe loop.

[14] Personal communication, D. Ellis (Comfortworks, Inc.) to Van Baxter, August 29, 2016. Estimated mature market selling price for Trilogy unit including DHW tank, installation and commissioning.

[15] Compares to ~$5100 for a typical (non-IHP and non-premium) WSHP unit as reported by E. C. Battocletti and W. E. Glassley in “Measuring the Costs and Benefits of Nationwide Geothermal Heat Pump Deployment,” prepared for the USDOE Geothermal Technologies Program, February 2013.

[16] Includes removal of existing WH tank, connecting WSHP to GHX headers, water piping connections between WSHP and DHW tank, connection to existing building air ducts and water pipes.

| | |
|---|---|
| mature market: | $21,000 |

Knoxville site baseline RTU/HP + electric WH system install cost estimate:

| | |
|---|---|
| New RTU unit: | $4,100[17] |
| Roof curb: | $1,500 |
| Structural: | $1,700 |
| Plans/Permits: | $2,000 |
| Crane: | $1,000 |
| Connection to existing ductwork: | $1,000 |
| Total: | $11,300 |

Except for the RTU, baseline installation cost estimates were based on costs given in the Gas Engine Heat Pump field demonstration report by Vineyard, at al.[18] Before the IHP was installed heating and cooling for the kitchen facility at the site was supplied by a central system serving the entire building. Due to the heavy internal loads in the kitchen (due to refrigerator/freezer units, cooking equipment, dishwasher, etc.), the existing system had inadequate cooling capacity during workdays. So, for the baseline system used in this comparison it is assumed that a new RTU/HP dedicated to the kitchen area would be installed requiring some structural modifications to the roof to accommodate the weight of the unit along with new ductwork from the RTU to the existing kitchen ductwork. For the baseline water heating, it was assumed that the existing electric WH would be used so no install costs related to WH were included.

Oklahoma City site installation (new building) cost estimates:[19]

Total system estimate:

| | |
|---|---|
| GHX actual (per installer billing): | $ 51,200 (~$10.2/bore ft) |
| Equipment (four WSHP units plus ERV): | $ 39,100 |
| Indoor GHX loop and DHW tank connections: | $ 6,500 |
| Totals: | $141,200 |

Subtotal estimate for one Trilogy IHP (assumes GHX loop with 1,250 bore ft total) :

| | |
|---|---|
| GHX: | $12,800 (~$10.2/bore ft.) |
| Equipment: | $ 9,800 |
| Indoor GHX loop and DHW tank connections: | $ 2,025 |
| Totals: | $24,625 |

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[17] Price for 4-ton Goodman RTU from Ingram's website: http://ingramswaterandair.com/commercial-units-commercial-package-heat-pump-c-45_170_173.html, accessed August 29, 2016

[18] Field Demonstration of Gas Heat Pump Rooftop Unit with Waste Heat Recovery for Water Heating. Ed Vineyard, Randall Wetherington, Mahabir Bhandari, and Jeff Munk. Oak Ridge National Laboratory, September 2105.

[19] Personal communication, D. Ellis (Comfortworks, Inc.) to Van Baxter, August 28, 2016. Total system equipment cost includes two Trilogy (IHP) WSHPs with 105 gal DHW tanks and two non-IHP WSHPs with thermostats and misc. materials along with one energy recovery ventilator (ERV) @$6,800. Ductwork cost was $50,700 for entire building; was assumed to be same for IHP and baseline installations.

Oklahoma City baseline RTU/HP + electric WH system install cost estimate:

| | |
|---|---|
| New RTU unit: | $4,300[20] |
| Roof curb: | $1,500 |
| Structural: | $1,700 |
| Plans/Permits: | $2,000 |
| Crane: | $1,000 |
| Connection to existing ductwork: | $1,000 |
| New 105 gal electric WH | $1,900[21] |
| Total: | $13,400 |

## F. GS-IHP Control Verification, Performance-Related Issues, and Installation and Maintenance

The Trilogy WSHP for the GS-IHP system includes an advanced, onboard control system that features VS compressor, indoor blower, GHX loop pump, and DHW loop pump capability. It also features recovery of normally rejected heat from the space cooling operation to provide domestic hot water for the building and year-round water heating capability at heat pump efficiency levels. These control strategies have successfully enabled both systems to function as designed and maintain space and hot water temperatures in the building with no complaints.

The only reported maintenance issue for the Knoxville site was failure of a main system control board at installation. CM provided a replacement board under warranty within a week and no further issues were encountered. There were two operation/control related issues we noted via observation of the performance data at the Oklahoma City site. In August and again in September the Trilogy WSHP unit went offline for just over 4 days (~101 hours) when a power surge or other event caused the controls to shut it down. There was no space cooling available to the residential units and water heating was by the HW tank backup electric heating elements during both periods. However, no one at the shelter reported any problems to either ClimateMaster or the installing contractor (Comfort Works, Inc.). In both cases the Trilogy began normal operation again after the thermostat was adjusted. But whether the adjustment was by an automatic recovery feature in the controls (after a default timeout) or someone at the shelter manually adjusted the setting is not known.

The only routine maintenance required for the Trilogy unit is air filter change out twice per year at an estimated cost of $40 each change ($80/y).

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[20] Price for 5-ton Goodman RTU from Ingram's website.

[21] Price quote from Home Depot in September 2016 for 105 gal electric WH ~$1500; assumed $400 for installation.

## V. Annual Performance Results – Knoxville site

Table 4 summarizes the overall GS-IHP performance monitoring results for the period from 2:00 pm on 8/18/2015 through midnight of 8/18/2016 along with the assumptions/limitations of the comparison. Only SC and WH operation data are included in the table because no SH operation was required during the test year at the Knoxville site. The data set was missing only a three day period from March 24, 8am to March 27, 11am.

**Table 4. Knoxville: GS-IHP summary performance comparison vs. baseline system**

| | GS-IHP | Baseline RTU + electric WH |
|---|---|---|
| Space Cooling (from SC and SC+WH modes) | | |
| Total Space Cooling Delivered (kWh) | 16729 | 16729 |
| Sensible Cooling Delivered (kWh) | 14227 | 14227 |
| Sensible heat ratio (SHR) | 0.85 | 0.85 |
| SC Energy Use (kWh); % savings vs. Baseline | 2165; 46.3% | 4032 |
| Space Cooling COP | 7.73 | 4.15 |
| Water Heating (from demand WH and SC+WH modes) | | |
| Total HW used (gal) | 19262 | 19262 |
| Average working day HW use (gal/d) | 78.3 | 78.3 |
| WH output from WSHP to WH tank (kWh) | 2730 | -- |
| Water Heating Delivered to Building (kWh) | 2106 | 2106 |
| Total WH Energy Use (kWh); % savings vs. Baseline | 646; 72.4% | 2340 |
| GS-IHP backup tank element energy use (kWh) | 1.5 | -- |
| Water Heating COP | 3.26 | 0.90[22] |
| Water heating COP excluding tank/line losses | 4.23 | 1.00 |
| | | |
| Misc. energy consumption from controls, etc. (kWh) | 151 | 151 |
| | | |
| **Overall** | | |
| **Energy Use (kWh)** | **2962** | **6519** |
| **% Energy savings** | **54.6%** | **--** |
| **Carbon Equivalent Emissions ($CO_2$ metric tons)**[23] | **2.04** | **4.49** |
| **$CO_2$ Emission Savings (metric tons)** | **2.45** | **--** |

Assumptions

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[22] Minimum energy factor (EF) rating for existing 50 gal electric storage WH manufactured before April 15, 2015 as rated per DOE test procedure https://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/27.

[23] Estimated using a kWh-to-$CO_2$ conversion factor of $6.89 \times 10^{-4}$ metric tons/kWh; taken from Energy Prices and Carbon Content (8/3/15 version) by Colin Weber.

1) Baseline RTU sensible heat ratio (SHR) - a measure of latent cooling or dehumidification capacity - is the same as that estimated for Trilogy WSHP.
2) Baseline RTU is a 48,000 Btu/h (4 ton) rated cooling capacity unit (see Table 1 for other ratings)
3) Baseline RTU fan power is 365 W/1000 cfm (taken from the current AHRI 210/240 ratings procedure[24])
4) Baseline RTU misc. energy use is the same as that measured for the Trilogy WSHP
5) Energy use for the combined SC+WH mode is divided between SC and WH proportional to the output capacities. Basically the COP for WH and SC in the combined mode is assumed to be the same. This has the effect of lowering the SC efficiency a bit (due to the higher condensing pressures required for the SC+WH mode) and raising the WH efficiency relative to the SC-only and dedicated WH mode efficiencies.
6) The Trilogy sensible cooling and subsequent SHR are calculated based on the cfm provided by the Trilogy unit, an assumption of 0.075 lbm/ft$^3$ air density, and measured return and supply air temperatures.
7) The baseline system is assumed to use the existing electric WH at the site; rated energy factor (EF) is assumed to be 0.9 (minimum EF required for electric WHs manufactured before April 1, 2015).

Note that the SC mode energy savings are likely somewhat conservative. This is due to the assumption that both the IHP and the Baseline RTU maintained similar comfort (sensible and latent SC loads) as discussed in section IV.C above. Since the RTU does not have a VS blower like the IHP it would likely have to consume more energy to meet the same latent SC loads.

Figure 13 provides a graphical comparison of the monthly average overall SC COPs for the GS-IHP and Baseline RTU/heat pump. The GS-IHP SC COPs in the plot include SC delivered in both SC-only and SC+WH modes.

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[24] Air-conditioning, Heating, and Refrigeration Institute, ANSI/AHRI Standard 210/240-2008 with Addenda 1 and 2, "*Performance Rating of Unitary Air-Conditioning & Unitary Heat Pump Equipment,*" March 2012.

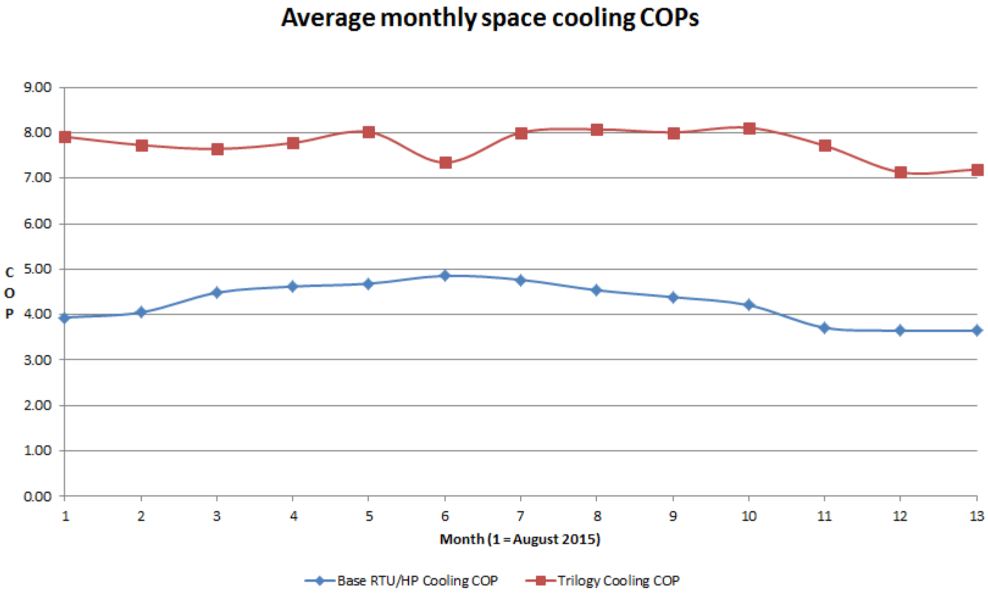

**Figure 13. Knoxville: Trilogy WSHP vs. Baseline RTU/heat pump SC monthly average COPs**

Table 5 provides a summary of the average COPs for the GS-IHP system for each of its active operating modes over the test year. Note that the overall SC mode COP for the GS-IHP system in Table 5 (8.0) does not include the impact of the SC energy delivered during the combined SC+WH mode. The GS-IHP SC COP reported in Table 4 (7.73) does include that impact, accounting for the slight difference in the COP values. But most of the SC load during the year (~92.5%) was delivered during SC-only mode (most efficient for SC). Table 5 also includes the estimated RTU SC COP for comparison. Note that the two WH mode COPs in Table 5 (SC+WH and demand WH) are based on the WH delivered at the exit of the Trilogy WSHP to the WH tank and connecting lines. Thus they are comparable to the WH COP excluding tank/line losses in Table 4. Most of the WH load was delivered during SC+WC mode (~67%), the most efficient for WH.

**Table 5. Knoxville: Approximate overall average GS-IHP COPs by operation mode**

| | GS-IHP SC-only mode | GS-IHP SC+WH mode[a] | GS-IHP demand WH mode[a] | Baseline RTU SC-only COP |
|---|---|---|---|---|
| Total period | 8.0 | 5.6 | 3.2 | 4.14 |

[a] Based on WH delivered from WSHP to WH tank (excludes tank & connecting line losses)

The primary reason the GS-IHP performed so much better than the baseline is that the entering water temperature (EWT) to the WSHP from the GHX loop was generally significantly more favorable than the outdoor air temperature (OAT) during hours when space cooling or demand WH operation was required at the site. Figure 14 compares the hourly OAT and EWT of the Trilogy in both modes. In the hottest parts of the summer the EWT was consistently cooler (by >20 °F) than the OD air which minimized the condensing pressure leading to improved SC mode efficiency. In winter months the EWT was much warmer than the OD air benefitting the GS-IHP WH mode efficiency. Figure 14 also shows that the EWT at the end of the monitoring period was essentially the same as in August 2015 when the unit began operating. This indicates that, despite the heavily SC-load dominated operation all year and addition of the antifreeze solution in January, there was no discernable warming of the ground surrounding the GHX bores during this first year of operation. It is possible that the GHX loop could have been somewhat shorter, reducing system cost though sacrificing some energy saving potential due to reduced efficiency.

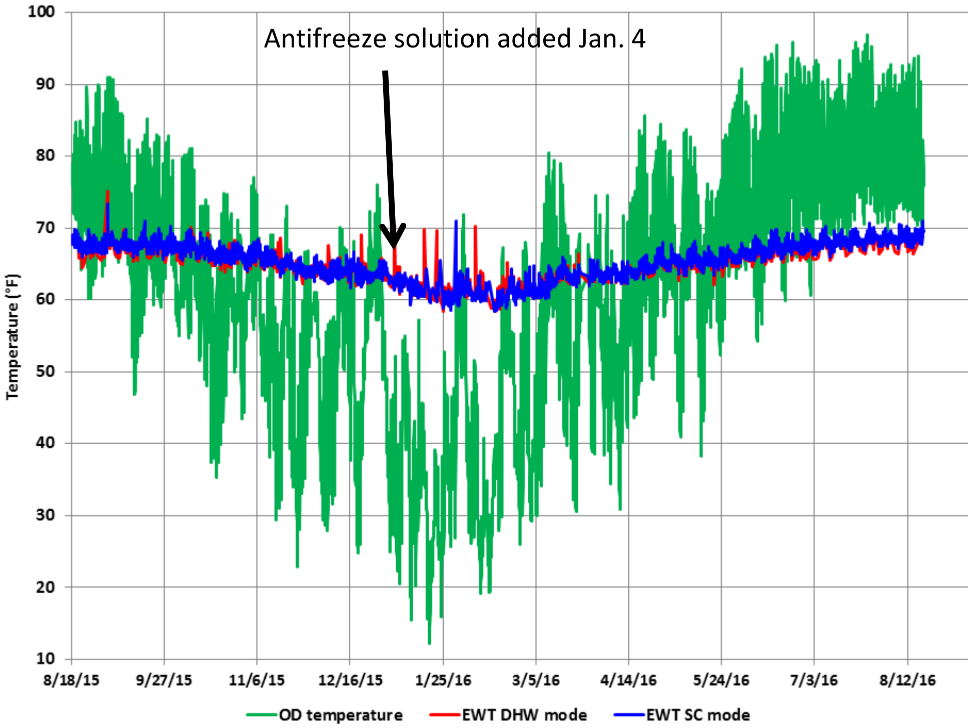

**Figure 14. Knoxville: Trilogy WSHP EWT vs. OAT**

Also, as a side note, the kitchen staff kept the SC set point fairly low as evidenced by the space temperature history during the test period, shown in Figure 15, below. During the occupied periods (week days) the air temperature in the kitchen ranged as low as ~64°F.

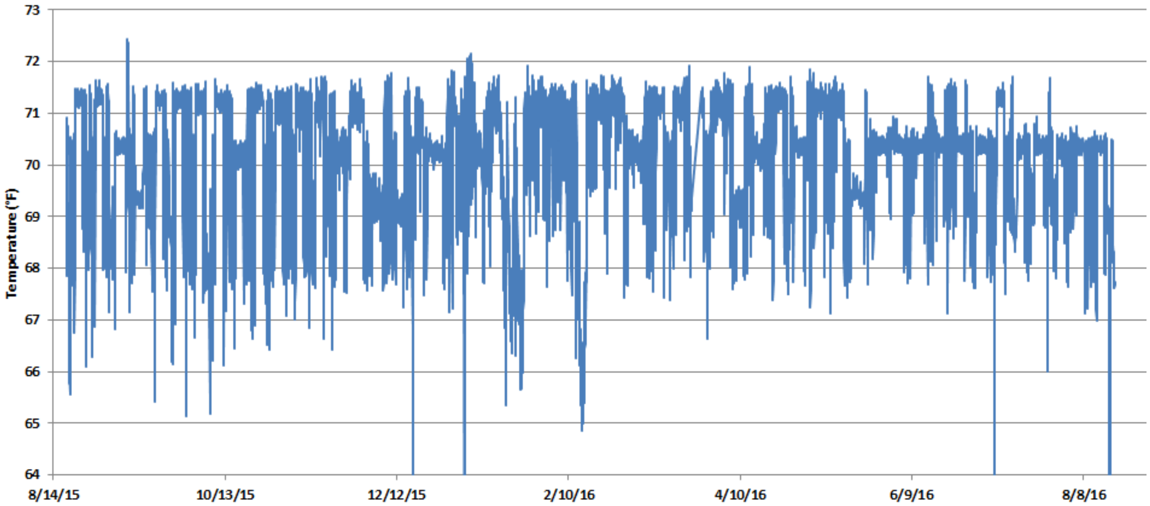

**Figure 15. Knoxville: Kitchen space temperature measured at thermostat during test year**

In addition to the energy savings, the GS-IHP system achieved significant reductions in hourly average kW demand at the Knoxville site. Monthly peak hour kW demand is shown in Table 6 for the GS-IHP and Baseline systems. The maximum average hourly demand each month for the GS-IHP ranged from 54% to 78% lower than that of the baseline system.

**Table 6. Knoxville: Peak hourly kW demand by month, GS-IHP vs. Baseline**

| Month | GS-IHP demand, kW | Date | Baseline demand, kW | Date |
|---|---|---|---|---|
| Aug. 18-31, 2015 | 1.705 | -- | 4.545 | -- |
| September 2015 | 2.923 | 9/2/15, noon-1pm | 4.349 | 9/2/15, 1-2pm |
| October 2015 | 1.642 | -- | 5.290 | -- |
| November 2015 | 1.888 | 11/6/15, noon-1pm | 5.444 | 11/10/15, 1-2pm |
| December 2015 | 1.603 | -- | 7.110 | -- |
| January 2016 | 1.593 | -- | 5.508 | -- |
| February 2016 | 1.538 | -- | 5.407 | -- |
| March 2016 | 1.664 | -- | 5.969 | -- |
| April 2016 | 1.510 | -- | 5.647 | -- |
| May 2016 | 1.778 | -- | 5.676 | 5/20/16, 2-3pm |
| June 2016 | 2.301 | 6/14/16, noon-1pm | 10.425 | 6/16/16, noon-1pm |
| July 2016 | 1.682 | -- | 5.557 | -- |
| Aug. 1-18, 2016 | 1.331 | -- | 5.280 | -- |
| Total period | 2.923 | 9/2/15, noon-1pm | 10.425 | 6/16/16, noon-1pm |

It can be noted, however, that perhaps the most significant factor influencing the IHP system peak demand at this specific location was the kitchen staff behavior. Figure 16 illustrates the hourly IHP system and tank element power and baseline RTU/HP system power along with outdoor temperature, hot water tank temperature (at top element location), the thermostat cooling set point temperature, and the hot water consumption for the week beginning August 30, 2015. [Note: the IHP and tank element power values are divided by 100 in order to make all the parameters fit on the chart.] Both the IHP and baseline system September peak demands occurred on Wednesday of that week. The IHP peak demand (purple line) is not coincident with the outdoor temperature (orange line). Rather, it coincides with the point where the kitchen staff lowered the thermostat set temperature (light blue line) from 68 °F to 66 °F causing the system to ramp up to almost maximum compressor speed (light purple line) for about a full hour to meet the sudden increase in space cooling demand. On the day before, with similar OD temperatures and slightly lower peak HW demand but no sudden set point reduction, the IHP peak was only about half (1.52 kW vs. 2.92 kW). In contrast the baseline system, which does not have variable capacity capability to improve efficiency, peak demand (red line) was estimated to be only about 0.2 kW lower (4.11 kW vs. 4.32 kW). Similar thermostat adjustments were largely responsible for the IHP system peaks in November and June as well. Had these occupant thermostat changes not occurred it is estimated that the IHP maximum monthly peak demands would have been in the 1.5 to 1.8 kW range every month. The average hourly compressor speed absent thermostat adjustments generally ranged from ~50% to ~70% of the maximum speed at this site.

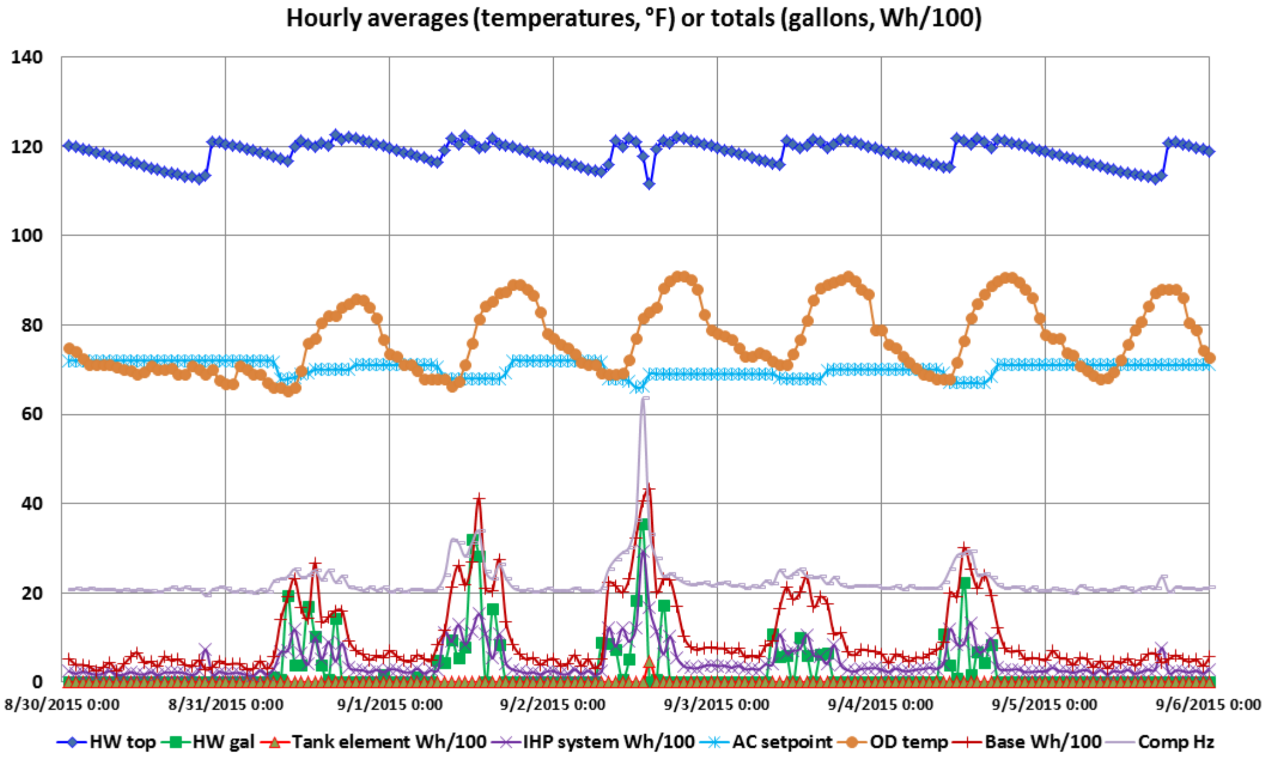

Figure 16. Knoxville: Maximum IHP hourly peak demand week

Energy cost savings for the Knoxville site were computed based on the energy and demand savings from Tables 4 and 6, and the commercial rate data from the Knoxville Utilities Board (KUB).[25] For the summer months of June, July, August and September, KUB charges $0.12171/kWh and $13.92/kW. For all other months the rates are $0.12130/kWh and $13.13/kW. Costs and savings for the GS-IHP vs. the Baseline are given in Table 7. Total energy cost savings were ~64%, about 65% of which are due to the lower demand charges.

**Table 7. Knoxville: GS-IHP HVAC/WH energy cost savings (8/18/15 – 8/18/16)**

| | **Baseline RTU/heat pump and electric WH** | **GS-IHP** |
|---|---|---|
| **Electricity consumption** | $792 | $360 |
| **Electricity demand** | $1,052 | $312 |
| **Total costs** | $1844 | $672 |
| **Energy cost savings vs. Baseline** | -- | $1172 |
| **%cost savings vs. Baseline** | -- | 63.6% |

## VI. Oklahoma City Performance Results

As noted above (see Section IV.B), the Oklahoma City DAQ system became functional for SH and SC mode data collection on January 31 but not for the WH modes until late April. Therefore monitored data are not available to support a full year's performance summary as was the case for the Knoxville site. So this section provides a summary of the IHP system performance vs. the baseline for each individual mode. Note that there are a number of gaps in the data as detailed below.

Data availability January through August 2016:

- January --- data collection began Jan. 31 at 8am; space heating data only
- February --- space heating data available all month
- March --- space heating data available all month
- April --- space heating and space cooling data available through April 28, 3pm
- May --- no data up through May 19, 1pm; all data available May 19 – May 31
- June --- data missing from June 10, 6pm through June 15, 6pm; all data available remainder of month
- July --- all data available

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[25] Knoxville Utilities Board, *General Power Rate – Schedule GSA*, July 2016. http://www.kub.org/wps/wcm/connect/3bfe2f80424c71338027b1d8d4cab33c/GSAJuly.pdf?MOD=AJPERES&CACHEID=3bfe2f80424c71338027b1d8d4cab33c

- August --- all data available except for August 12-16 outage due to control issue (described in section IV.F)
- September --- data through September 19, 1pm except for September 3-7 outage due to control issue

The assumptions listed under Table 4 for the Knoxville site data analyses (reiterated below with two differences as noted) also apply to the Oklahoma City site data analyses.

Assumptions

1) Baseline RTU SHR is the same as that estimated for Trilogy WSHP.
2) Baseline RTU is a 60,000 Btu/h (5 ton) rated cooling capacity unit (48,000 Btu/h or 4 ton for the Knoxville site due to lower design load)
3) Baseline RTU fan power is 365 W/1000 cfm (taken from the current AHRI 210/240 ratings procedure)
4) Baseline RTU misc. energy use is the same as that measured for the Trilogy WSHP
5) Energy use for the combined SC+WH mode is divided between SC and WH proportional to the output capacities. Basically the COP for WH and SC in the combined mode is assumed to be the same. This has the effect of lowering the SC efficiency a bit (due to the higher condensing pressures required for the SC+WH mode) and raising the WH efficiency relative to the SC-only and dedicated WH mode efficiencies.
6) The Trilogy sensible cooling and subsequent SHR are calculated based on the cfm provided by the Trilogy unit, an assumption of 0.075 lbm/ft$^3$ air density, and measured return and supply air temperatures.
7) The baseline system is assumed to require a new electric WH; rated energy factor (EF) of 0.94 (minimum EF required for electric WHs manufactured after April 1, 2015). For Knoxville we assumed the original electric WH (installed prior to April 2015) was used; EF = 0.9.

Tables 8-10 summarize the Oklahoma City GS-IHP performance for SH, SC, and WH operation, respectively.

As shown in Table 8, the IHP system demonstrated an overall SH COP of almost 5.0 and energy and cost savings of ~52% over the 61.7 days for which data were available. Energy cost savings for the Oklahoma City were computed using the standard residential service rates from the Oklahoma Gas and Electric Company (OGE).[26] OGE charges a standard rate of \$0.0573/kWh year-round with a slightly higher rate (\$0.068) in June-September for consumption in excess of 1400 kWh/month and a lower rate (\$0.0173) in November-May for consumption in excess of 600 kWh/month. For purposes of our analyses we assumed the standard rate applied all year. Total electric cost savings for the monitored unit were ~\$43. Assuming the average SH daily load and efficiency for the entire heating season would be the same as

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[26] Oklahoma Gas and Electric Company, *Standard Pricing Schedule: R-1 Residential Service*, August 2012. https://oge.com/wps/wcm/connect/de21b39f-2d52-402f-82e6-a6826999d724/3.00+R-1.pdf?MOD=AJPERES&CACHEID=de21b39f-2d52-402f-82e6-a6826999d724

that for the monitored period, total SH energy and cost savings are estimated to be ~2060 kWh and $118. Since there are two IHP units in the building the SH cost savings would double to ~$236.

**Table 8. Oklahoma City: SH performance comparison, IHP vs. Baseline RTU/HP**

| Month | IHP COP | SH Delivered kWh | IHP SH Energy use kWh | Baseline RTU Energy use kWh | IHP Energy Savings % | IHP SH Energy cost $ | Baseline RTU Energy cost $ | IHP Energy cost Savings % |
|---|---|---|---|---|---|---|---|---|
| Jan 31 | 4.86 | 26.93 | 5.54 | 10.37 | 46.6% | $0.32 | $0.59 | 46.6% |
| Feb | 4.85 | 2101.82 | 433.43 | 915.40 | 52.7% | $24.84 | $52.45 | 52.7% |
| Mar | 5.04 | 1062.94 | 211.02 | 426.51 | 50.5% | $12.09 | $24.44 | 50.5% |
| Apr 1-28 | 5.27 | 263.43 | 49.94 | 99.99 | 50.0% | $2.86 | $5.73 | 50.0% |
| Total | 4.94 | 3455.12 | 699.94 | 1452.57 | 51.8% | $40.11 | $83.21 | 51.8% |

For SC operation data was available for 117.6 days, over which the IHP demonstrated a COP of ~6.9 with almost 50% energy and electric cost savings compared to the estimated performance of the baseline RTU (Table 9). The delivered SC energy to the building is a combination of the SC delivered in two modes; SC only and SC+WH; ~87% of the total SC load was delivered in SC-only mode operation. Total electricity cost savings for the monitored unit were ~$105. It can be noted that OGE also offers residential customers a time-of-use (TOU) rate option for June-October; from 2-7pm the electricity use rate is $0.14/kWh and for all other hours it is $0.027/kWh. With the TOU rate, both the IHP SC energy $ and % cost savings for the period would drop slightly to ~$100 and ~50%, respectively. Note that the measured SC savings at this site are also likely to be somewhat conservative due to the assumption that the Baseline RTU could maintain similar comfort levels as that provided by the IHP (see discussion in section IV.C).

Assuming the average SC daily load and efficiency for the entire cooling season would be the same as that for the monitored period, total SC energy and cost savings are estimated to be ~2760 kWh and ~$158. Since there are two IHP units in the building the SH cost savings would double to ~$316.

**Table 9. Oklahoma City: SC cooling performance comparison, IHP vs. Baseline RTU/HP**

| Month | IHP COP | Total SC Delivered kWh | Total IHP SC Energy use kWh | Baseline RTU Energy use kWh | IHP Energy Savings % | IHP SC Energy cost $ | Baseline RTU Energy cost $ | IHP Energy cost Savings % |
|---|---|---|---|---|---|---|---|---|
| Apr 1-28 | 7.17 | 98.48 | 13.73 | 25.92 | 47.0% | $0.79 | $1.49 | 47.0% |
| May 19-31 | 8.39 | 950.14 | 113.19 | 247.30 | 54.2% | $6.49 | $14.17 | 54.2% |
| June[a] | 7.08 | 3697.49 | 522.51 | 1045.08 | 50.0% | $29.94 | $59.88 | 50.0% |
| July | 6.60 | 4594.56 | 695.99 | 1356.30 | 48.7% | $39.88 | $77.72 | 48.7% |
| Aug[b] | 6.80 | 3229.54 | 475.22 | 939.58 | 49.4% | $27.23 | $53.84 | 49.4% |
| Sept[c] | 8.05 | 366.95 | 45.56 | 98.87 | 53.9% | $2.61 | $5.67 | 53.9% |
| Total | 6.93 | 12937.16 | 1866.19 | 3713.05 | 49.7% | $104.32 | $212.76 | 49.7% |

[a] gap in data from June 10-15.

[b] gap in data from August 12-16.

[c] gap in data from September 3-7.

Estimated WH performance at Oklahoma City is given in Table 10 (note that performance at this site is estimated assuming that the ratio of WH delivered to the building is the same as measured at the Knoxville site as discussed earlier in Section IV.C). Operation data was available for 109.6 days total. For that period the IHP's estimated WH mode COP was ~4.449 with ~79% energy and electricity cost savings compared to the baseline electric WH, while delivering almost 189 gal/d of hot water to the residential units in the building (~19 gallons/day/unit). The delivered WH energy to the building is a combination of the WH delivered to the building in two modes: dedicated WH and SC+WH with over 80% coming during the SC+WH operating mode. Total electricity cost savings for the monitored unit were ~$131. With the TOU rate assumption, IHP WH energy $ and % cost savings for the period would drop slightly to ~$125 and ~75%, respectively. Modification of the Trilogy controls, e.g., to delay WH operation until after peak periods, limit maximum compressor and fan speeds during peak periods, etc., could yield higher energy cost savings with the TOU rate.

Assuming the average WH daily load and efficiency for the entire year would be the same as that for the monitored period, total WH energy and cost savings are estimated to be ~12460 kWh and ~$714. Since there are two IHP units in the building the SH cost savings would double to ~$1428.

**Table 10. Oklahoma City: WH performance comparison, IHP vs. Baseline RTU/HP**

| Month | Daily hot water use, gal/d | IHP COP | Total WH Delivered to bldg. kWh | Total IHP WH Energy use kWh (tank element kWh) | Baseline WH Energy use kWh | IHP WH Energy cost $ | Baseline WH Energy cost $ |
|---|---|---|---|---|---|---|---|
| May 19-31 | 161 | 4.12 | 127.17 | 30.84<br>(0.21) | 133.19 | $1.77 | $7.63 |
| June[a] | 167 | 4.27 | 286.64 | 67.09<br>(3.68) | 302.64 | $3.84 | $17.34 |
| July | 182 | 4.72 | 1008.41 | 213.81<br>(4.99) | 1062.5 | $12.25 | $60.88 |
| Aug[b] | 181 | 4.45 | 808.35 | 181.59<br>(9.77) | 853.48 | $10.41 | $48.909 |
| Sept[c] | 280 | 4.12 | 530.84 | 128.94<br>(0.68) | 564.25 | $7.39 | $32.33 |
| Total<br>% savings | 189 | 4.44 | 2761.42 | 622.28<br>(19.11)<br>78.7% | 2916.05 | $35.66 | $167.09<br>78.7% |

[a] gap in data from June 10-15.

[b] gap in data from August 12-16.

[c] gap in data from September 3-7.

Table 11 provides a summary of the average COPs for the Oklahoma City GS-IHP system for each of its active operating modes over the test year. Note that the SC COP for the GS-IHP system in Table 9 above (6.93) is very close to both the SC-only and SC+WH mode COPs (7.0) as seen in Table 11. About 88% of the total SC load was delivered in the SC-mode. Note also that the two WH mode COPs in Table 11 (SC+WH and demand WH) are based on the WH delivered at the exit of the Trilogy WSHP to the WH tank and connecting lines. The WH loads in Table 10 are "as delivered to the WH tank" and the COPs, thus, lower than those in Table 11 since they include the tank and connecting line losses. Table 11 also includes estimated RTU SC and SH COPs at the Oklahoma City site for comparison.

**Table 11. Oklahoma City: Approximate overall average GS-IHP COPs by operation mode**

|  | GS-IHP SH-mode | GS-IHP SC-only mode | GS-IHP SC+WH mode[a] | GS-IHP demand WH mode[a] | Baseline RTU SC-only COP | Baseline RTU SH COP |
|---|---|---|---|---|---|---|
| Total period | 4.9 | 7.0 | 7.0 | 4.8 | 3.5 | 2.4 |

[a] Based on WH delivered from WSHP to WH tank (excludes tank & connecting line losses)

As for the Knoxville site, the entering water temperature (EWT) to the WSHP from the GHX loop was generally significantly more favorable than the outdoor air temperature (OAT) during hours when SH, SC, or WH operation was required. Figure 17 compares the hourly OAT and EWT of the Trilogy for these operating modes (combined SC+WH mode does not use the GHX). In the hottest parts of the summer the EWT was consistently cooler (by ~5-25 °F) than the OD air which minimized the condensing pressure leading to improved SC mode efficiency. In winter months the EWT was warmer than the OD air on average benefitting the GS-IHP SH and WH mode efficiency.

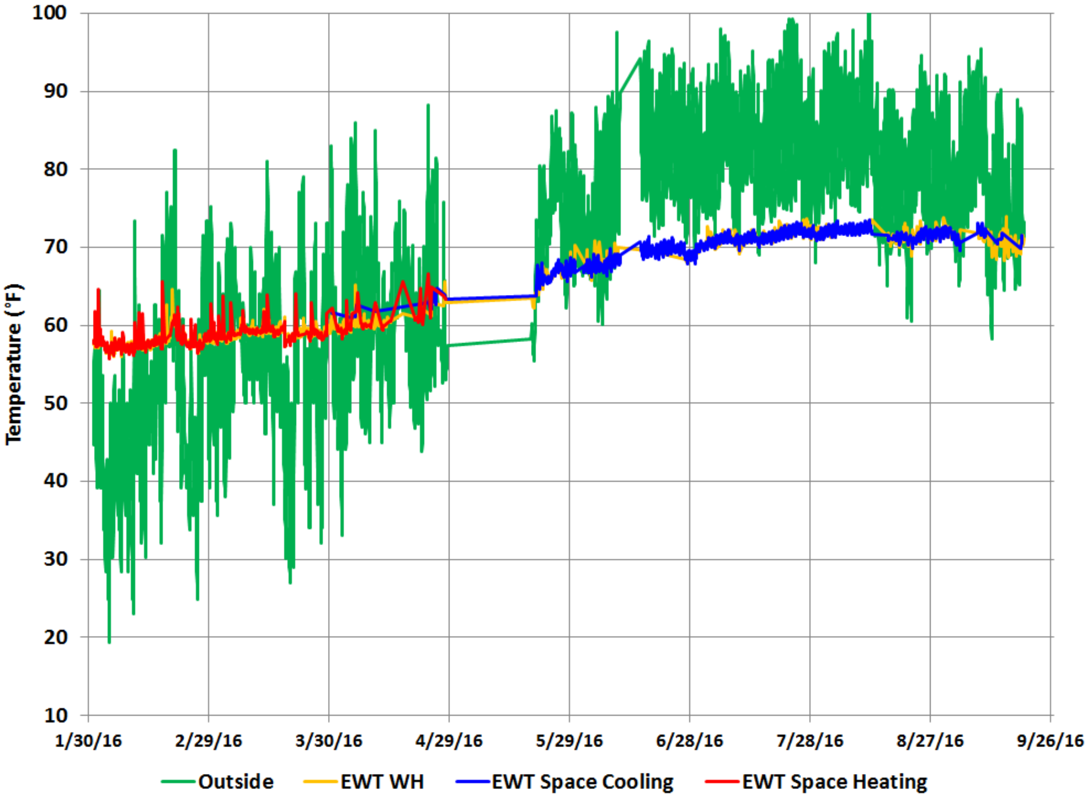

Figure 17. Oklahoma City: Trilogy WSHP EWT vs. OAT

Monthly hourly average peak kW demand at the Oklahoma City site is shown in Table 12 for the GS-IHP and Baseline systems.

**Table 12. Oklahoma City: Peak hourly kW demand by month, GS-IHP vs. Baseline**

| Month | GS-IHP demand, kW | Date | Baseline demand, kW | Date |
|---|---|---|---|---|
| January | 0.937 | -- | 2.869 | -- |
| February | 3.388 | 2/27/16, 4-5 am | 10.283 | 2/26/16, 4-5 am |

| Month | GS-IHP demand, kW | Date | Baseline demand, kW | Date |
|---|---|---|---|---|
| March | 3.139 | 3/19/16, 1-2 am | 10.574 | 3/19/16, 2-3 am |
| April | 4.437 | 4/13/16, 6-7 pm | 7.302 | 4/2/16, 4-5 am |
| May | 2.289 | 5/25/16, 6-7 pm | 6.605 | 5/28/16, 4-5 pm |
| June | 6.367 | 6/14/16, 5-6 pm | 7.960 | 6/14/16, 5-6 pm |
| July | 5.671 | 7/27/16, 5-6 pm | 9.869 | 7/25/16, 6-7 pm |
| August | 7.024 | 8/3/16, 5-6 pm | 9.144 | 8/3/16, 4-5 pm |
| September | 4.315 | -- | 8.070 | -- |
| Total period | 7.024 | 8/3/16, 5-6 pm | 7.201 | 2/26/16, 4-5 am |

Comparing Table 12 to Table 6 it can be noted that the Trilogy system peak demand was generally higher at the Oklahoma City site than that experienced at the Knoxville site. This can be seen in Figures 18-21 below for February, June, July, and August peak weeks, respectively (compare to Figure 16 which illustrates a peak week at the Knoxville site). There are a number of factors contributing to this difference. One is that the Trilogy WSHPs at the homeless shelter were configured to deliver a maximum cooling capacity of 5 tons due to the higher design loads at the shelter vs. at the commercial kitchen in Knoxville. The higher SC loads at the shelter required the Trilogy to run at generally higher compressor drive frequencies (Hz) and, thus, higher compressor speeds, reaching peaks of almost 70 Hz (~4200 compressor rpm) at times. In contrast, the Trilogy unit at the Knoxville site seldom experienced compressor drive frequencies higher than about 40 Hz. Hourly SH or SC energy use (aka hourly power demands) for the IHPs at the Oklahoma City location were therefore higher.

Secondly, WH demands at the shelter were larger and more constant than at the Knoxville kitchen facility. This resulted in more frequent use of the backup electric elements in the WH tanks than was seen in Knoxville. While the total usage of the elements at the shelter was modest (~19 kWh from May-September), at times element operation coincided with peak AC demand periods. This resulted in occasional sharp, short term peaks in the summer months for the IHP system as seen in Figures 19-21 when the Trilogy system peak approached 6-7kW. [Note: as for Figure 16, the IHP and tank element power values in Figures 18-21 are divided by 100.] Application of control strategies to prohibit or minimize back-up WH element usage during peak times could hold the IHP hourly peaks to <4 kW.

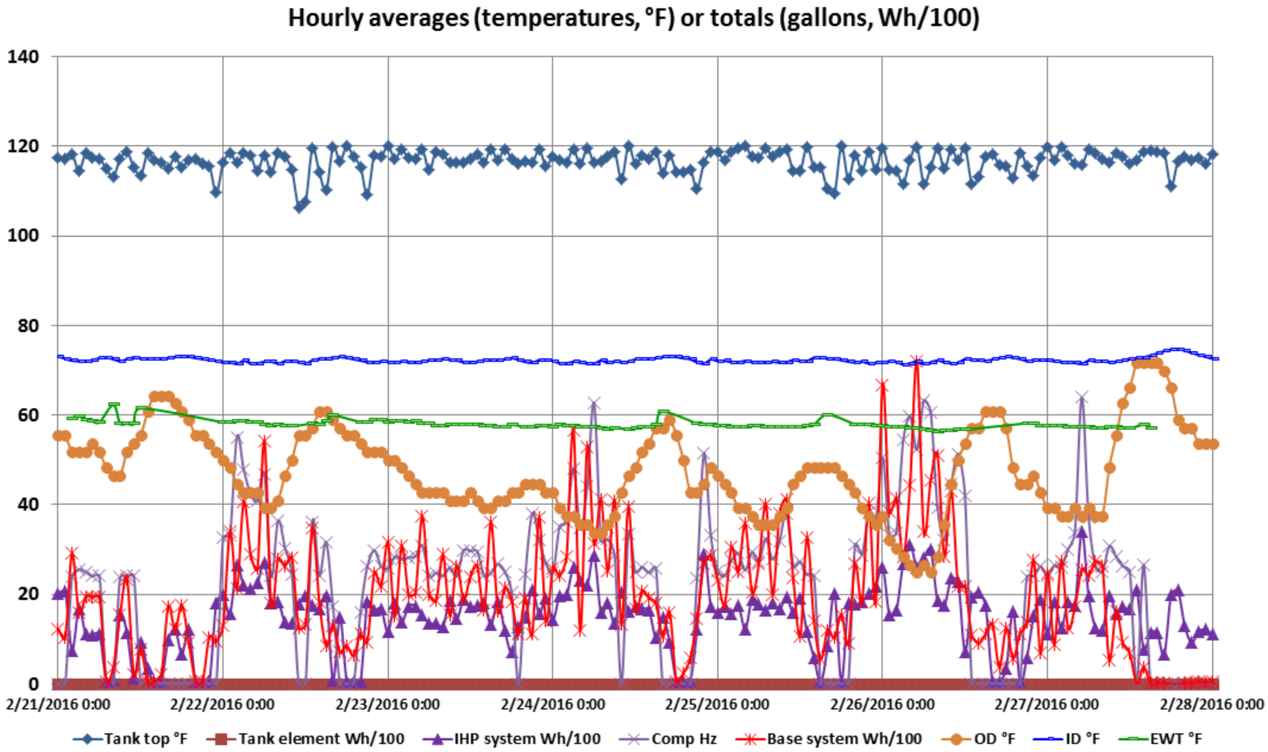

**Figure 18. Oklahoma City: Maximum SH season IHP hourly peak demand week**

Note that for the February peak week plot in Figure 18 there was no IHP system WH energy delivery data for reasons noted elsewhere in the report. The IHP energy use data, however, do reflect WH mode operation as can be seen most clearly by the data for the last half of February 27. The compressor drive Hz (light purple line) plotted in Figure 18 is only for the SH mode and note that it drops to zero but the IHP energy use (dark purple line) continues to show it in operation. During that period the IHP was operating in WH mode only. The back-up electric elements in the IHP WH tank were also being monitored but as can be seen by the heavy dark red line along the x-axis in Figure 18, the elements were never active throughout this week – e.g., the entire WH load was served by the Trilogy unit both for this peak week and essentially for the entire January 31 through April 28 period. Total backup element energy use recorded by the DAQ for January-April was only ~1 Wh.

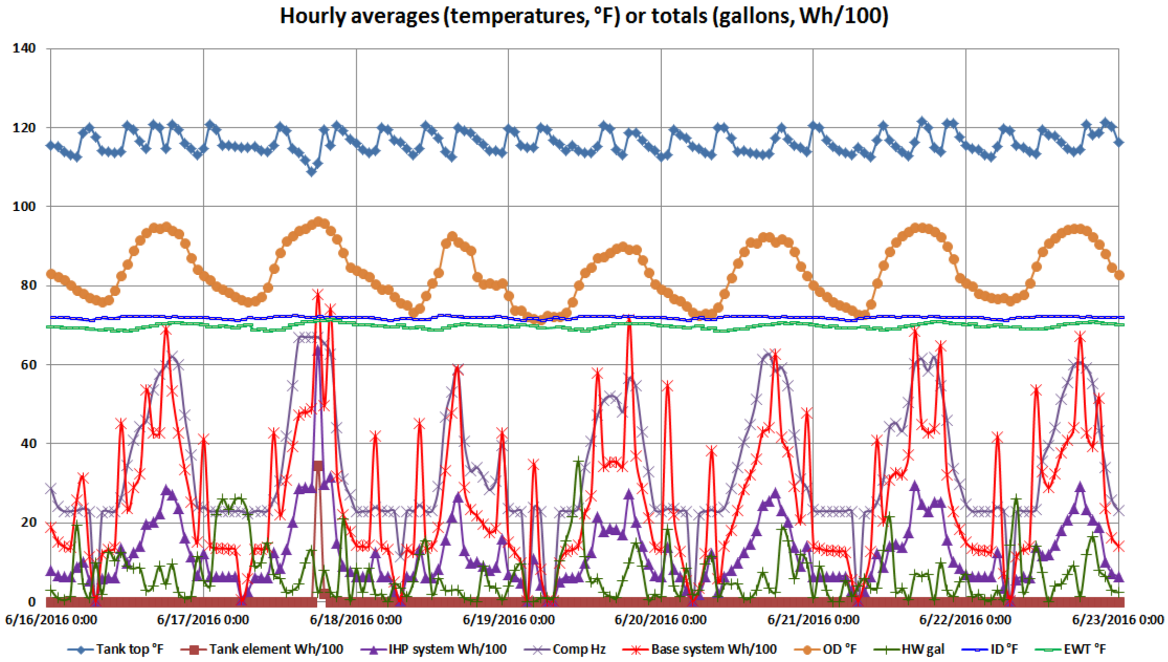

Figure 19. Oklahoma City: June IHP hourly peak demand week

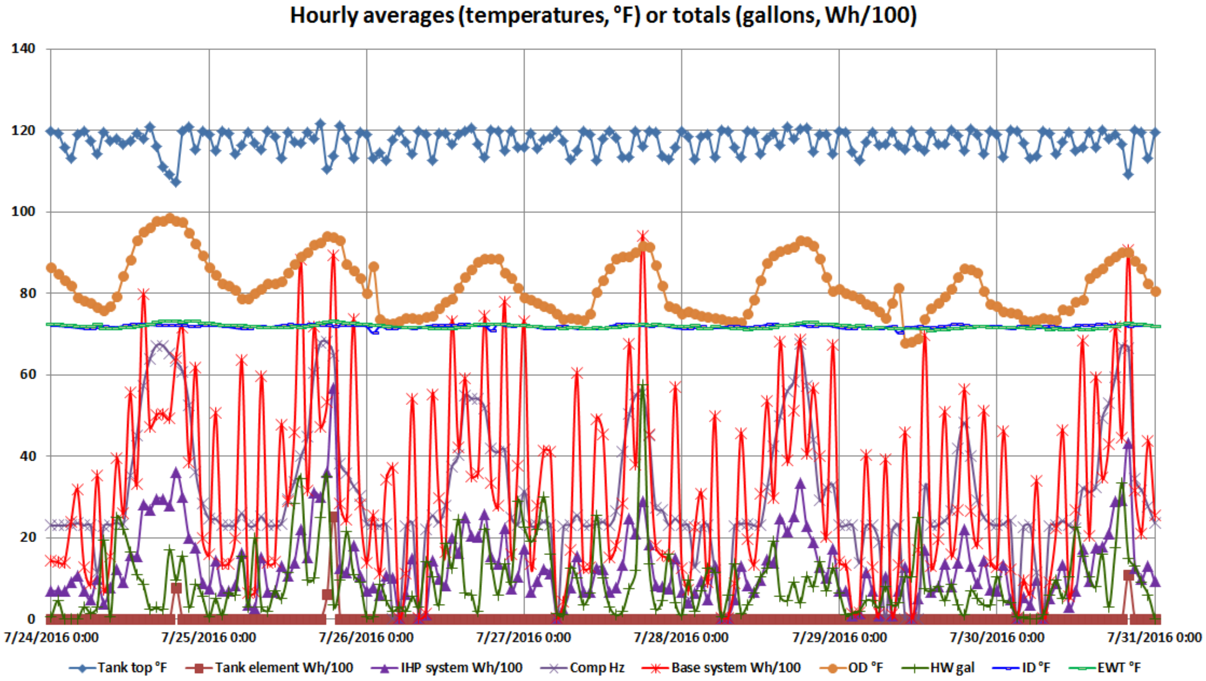

Figure 20. Oklahoma City: July IHP hourly peak demand week

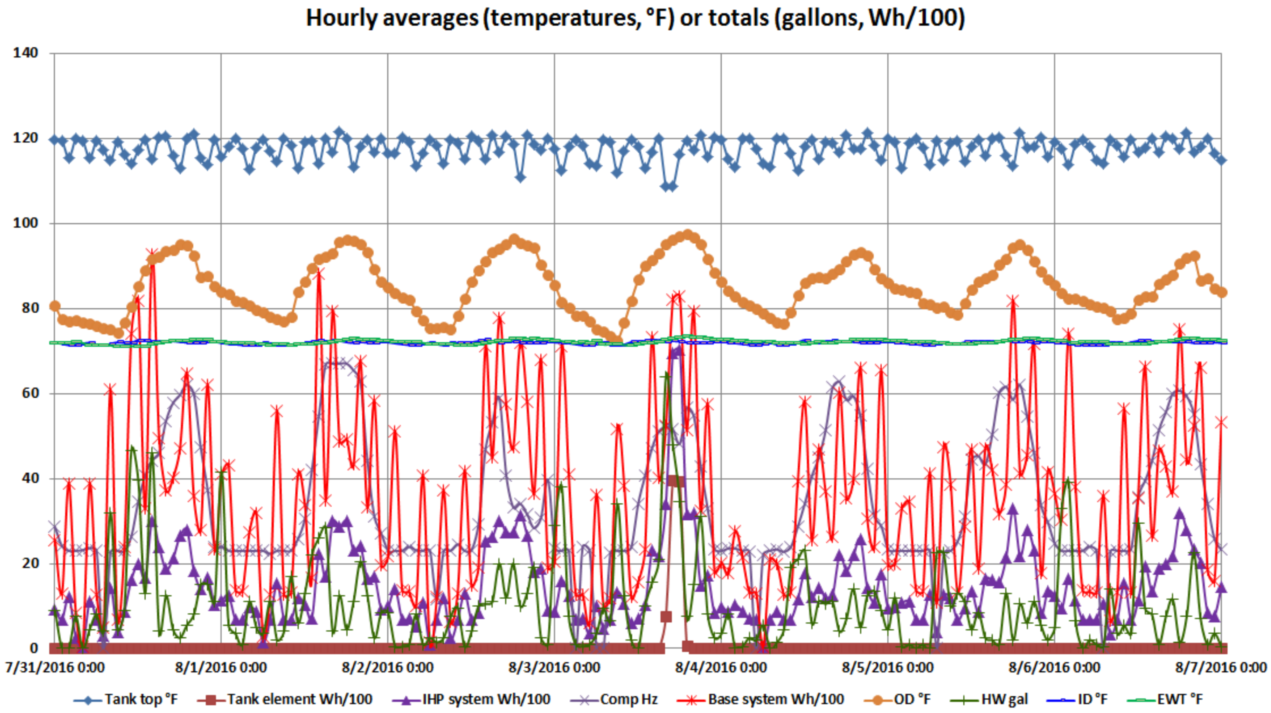

**Figure 21. Oklahoma City: August IHP hourly peak demand week**

## VII. Cost analysis for Knoxville site

A payback analysis is given in Table 13, based on the Knoxville system design. Equipment cost details for the base RTU/HP system and high and low costs for the GS-IHP are given in section IV.E above. Three GS-IHP cost assumptions are given in Table 13. The "high" cost assumption uses the GHX cost as billed by the contractor for the Knoxville site. A "low" cost assumption is given based on the contractors' estimate that GHX cost could have been up to one third of the actual cost absent the "out of normal" conditions experienced as discussed in IV.E. Next is a "mature market" cost assumption based on experience with a large number of installations in Oklahoma. Finally, an alternative GHX financing approach is considered. For this case it is assumed that the utility installs and owns the GHX (e.g. under an ESPC or utility energy savings contract (USEC), etc.).[27] A GHX cost recovery charge of 2% of the GHX installation cost (for the mature market case) is added to the electric bill, reducing the total annual

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[27] An example of this approach is a program being undertaken by Western Farmer's Electric Cooperative, described in the article "In the Loop" by Robert Cunningham (October 5, 2015) in the Rural Electric Magazine web edition, http://remagazine.coop/in-the-loop/, accessed August 31, 2016. A quote taken from the article --- "*Meanwhile, Western Farmers Electric has been working with several distribution co-ops to test the economics of a "thermal service" program option where the latter would build, own, and maintain the underground loop and provide it to their members as a utility service at a fixed monthly rate. . . . . . this option presents opportunities like the chance to deploy new and innovative business models to deliver the benefits of GSHPs to members and provide a new, stable revenue stream.*"

energy cost savings to the building owner.[28] Using the energy cost savings from Table 7, the payback for the GS-IHP ranges from ~8.5 to >30 years for the low and high GHX cost ranges assuming the building owner pays the cost of the GHX installation up front. Assuming the utility installs and owns the GHX (building owner pays only for the Trilogy and associated indoor installation); the payback period could drop to ~0.3 year.

**Table 13. Payback analysis - Knoxville**

| | Equipment costs ($) | | GHX installed cost ($) | Total Cost (S) | Cost Difference ($) | Energy Cost Savings ($) | Payback (yrs) |
|---|---|---|---|---|---|---|---|
| | Price | Installation | | | | | |
| **Conventional RTU/HP and electric WH** | 4,100 | 7,200 | na | 11,300 | | | |
| **GS-IHP; high GHX cost assumption** | 9,800 | 1,600 | 38,000 | 49,400 | 38,100 | 1172 | **32.5** |
| **GS-IHP; low GHX cost assumption** | 9,800 | 1,600 | 15,000 | 26,400 | 15,100 | 1172 | **12.9** |
| **GS-IHP; mature market cost** | 9,800 | 1,600 | 9,600 | 21,000 | 9,700 | 1172 | **8.3** |
| **GS-IHP; mature market GHX cost; utility owns GHX assumption** | 9,800 | 1,600 | na | 11,400 | 100 | 980 | **0.1** |

[a] Utility adds cost recovery surcharge totaling 2% of GHX installation cost per year to bill ($192).

# VIII. Summary Findings and Recommendations

## A. Overall Technology Assessment at Demonstration Facility

For the August 2015 through August 2016 period, the Knoxville site GS-IHP provided 53.7% total source energy savings compared to a baseline electric RTU/heat pump and electric WH. Peak demand savings ranged from 54% to 78% per month. Energy savings of 54.6% and energy cost savings of 55.9% have been achieved (about evenly split between reduced demand charges and electricity consumption savings). The GS-IHP also saved a significant amount of carbon emissions - ~2.45 metric tons for the August 2015 to August 2016 test year. If trading for carbon credits ever becomes a reality, additional cost savings would be realized. These savings significantly exceeded the project technical performance

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[28] The 2% figure was chosen based on the typical default rate for such on bill financing (OBF) programs as noted in the report "Measuring the Costs and Benefits of Nationwide Geothermal Heat Pump Deployment," by E. C. Battocletti and W. E. Glassley, prepared for the USDOE Geothermal Technologies Program, February 2013.

goal of ≥45% energy and carbon emission reductions. For this site, no SH loads were experienced; only SC and WH operation was required for the entire test year.

For the Oklahoma City site delays in completing installation of the DAQ system prevented collection of a full year of performance data. However enough data was obtained to allow a reasonable estimate of SH, SC, and WH energy savings and efficiency vs. the baseline system.

- SH: from Table 8, total energy savings of ~753 kWh (~52%) and average COP of ~4.9
- SC: from Table 9, total energy savings of ~1847 kWh (~50%) and average COP of ~6.9
- WH: from Table 10, total energy savings of ~2293 kWh (~78%) and average COP of ~4.4

Over the actual monitoring period, the GS-IHP at the site demonstrated total site electricity savings of ~4890 kWh (~60%) and carbon emission savings of ~3.4 metric tons, greatly exceeding the project technical goal. Assuming that the daily average loads and COPs above are the same for the balance of the year for each mode it is estimated that total annual energy savings would be ~12,460 kWh with carbon emission savings of ~8.6 metric tons. Note that these numbers can be assumed to be double (~24,900 kWh and ~17.2 metric tons) since the shelter building had two GS-IHP units (the second unit was not monitored). Note that the WH savings indicated above are estimated assuming that the system at Oklahoma City experienced the same HW tank and connecting line standby heat losses (as a percentage of the total load) that were measured at the Knoxville site.

This field study successfully demonstrated the energy savings, environmental savings, and operational benefits of the GS-IHP technology for small commercial building applications. Both demonstration systems significantly exceeded the project technical objectives of >45% energy and carbon emission savings (>50% at both sites). Best applications of the GS-IHP system are buildings or specific small zones of buildings that have high hot water loads coincident with high space cooling loads.

Payback analyses were conducted for the Knoxville site system based on the annual energy savings demonstrated. The specific site conditions (limited area, local regulations, etc.) caused drilling costs to be about 3 times higher than typical for the area. For the actual GHX cost, simple payback vs. the baseline RTU/HP/electric WH system were >30 years (Table 13). With more typical GHX costs for the area the payback is approximately 13 years. For a “mature market” cost assumption based on experience in Oklahoma for a large number of installations the payback drops to ~8 years, still likely higher than acceptable for most commercial building owners. Assuming an alternative GHX financing option where the local utility (or other entity) installed and owned the GHX loop and amortized the cost via a surcharge on the electric bill were available, system payback could be reduced to ~0.1 year.

The only reported service need during the duration of the field test was the failure of the main control board at start up in Knoxville. The manufacturer provided a replacement under the warranty and no further incidents were experienced at either site.

## B. Market Potential and Recommendations

Based on demonstrated performance at the Knoxville site, if applied nationally to all appropriate commercial building spaces, GS-IHPs could save 0.084 quads of source energy vs. a 13 SEER RTU/heat pump and electric WH baseline. The actual utility bill savings for a building owner will depend on a number of factors, most notably the building's climate region, HVAC and DHW load profiles, and regional utility rates. As noted earlier, best performance and highest energy and energy cost savings would occur in applications that have high water heating loads coincident with high space cooling loads (commercial kitchens, laundries, restaurants, dormitory-like buildings, etc.).

These particular demonstrations were located in Knoxville and Oklahoma City. The Knoxville site was a small commercial kitchen which experienced a year-round SC load and fairly heavy HW demands during the work week (M-F). At Oklahoma City, a homeless shelter (dormitory-like facility) was used which featured relatively balanced SH and SC and WH loads with SC being the largest. Both sites allowed the GS-IHP to take advantage of its combined SC+WH mode featuring fairly extensive recovery of the normally wasted system condenser heat for water heating.

The economics of GS-IHPs will vary from site to site for several reasons, including:

- Regional differences in drilling costs, local site conditions and requirements, and financing options can cause the GHX loop installation costs to vary over a wide range even within a given region. Where local site conditions are unfavorable (restricted area, local permitting/regulation restrictions, etc. as experienced at the Knoxville site) GHX installation costs can be prohibitive

- Local electricity rate structures may limit the operating cost savings achievable, leading to higher payback periods.

Increasing the adoption of high-efficiency integrated HVAC/WH systems like the GS-IHP will require a change in the way HVAC contractors, design engineers, and building owners and operators consider them due to their increased installation cost. Raising awareness of the availability and the potential lifetime energy savings of GS-IHPs may encourage more industry professionals to evaluate them for their buildings, and determine whether the systems offer an acceptable payback based on climate, operations, building design, etc. Additionally, system designers have difficulty using popular building modeling tools to evaluate nonconventional equipment.

The following actions are recommended for promoting adoption of GS-IHP technology, including:

For Developers of Building Energy Modeling Tools:

- Design specific equipment modules for GS-IHP and include as an option within the modeling software

For DOE and Other Efficiency Organizations:

- Facilitate quick energy savings calculations by developing a simple set of regional climate maps estimating equipment runtimes for different scenarios

- Develop best practice guides based on evaluations against different baseline equipment and building types.

For Electric Utilities:

- Educate commercial customers on the life-cycle cost of GS-IHP technologies and include them in available grant, incentive, or financing programs.

For Local/State Government Agencies, Electric Utilities, Other Efficiency Organizations:

- Consider promoting and/or establishing specific financing options for GHX loops for commercial customers

- Consider promoting and/or establishing incentives for GS-IHP systems for commercial customers

## IX. Acknowledgements

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# Energy Trust of Oregon

## Manufactured Home Replacement Pilot Evaluation

August 12, 2020

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# 1. Executive Summary

## 1.1 Overview and Methods

Energy Trust of Oregon's (Energy Trust) Manufactured Home Replacement Pilot began in June of 2017 and is a collaborative effort among several stakeholders. The Pilot offers financial and other support to replace pre-1994, inefficient manufactured homes with new, energy-efficient manufactured homes. The Pilot began targeting replacements in three Oregon manufactured housing parks and has since expanded to offer the opportunity to manufactured housing homeowners on private land. The Pilot staff and partners include:

- Energy Trust: Conducts outreach, coordinates stakeholders, supports households in the replacement process, and provides a financial incentive for qualifying replacements.
- CLEAResult: Acting as an implementer for the Pilot, conducts outreach and supports households in the replacement process.
- Craft3: Offers a low-interest loan for households who do not own their land. They conduct outreach, provide financial counseling, and support participants.
- Community and Shelter Assistance Corp. (CASA) of Oregon: CASA arranges financing and provides support to purchase manufactured home parks and establish them as cooperatives. CASA recruits new participants and provides support to homeowners.
- Earth Advantage: Conducts pre-inspections of manufactured homes to determine eligibility and support an energy savings impact analysis.
- NeighborWorks Umpqua: Purchases manufactured home parks and operates them as a nonprofit. Residents own their homes and lease the land. NeighborWorks helps homeowners in their park navigate the replacement process.
- The United Community Action Network (UCAN): UCAN is a Community Action (CAP) agency that offers funds in the form of a subsidy to qualifying households to facilitate their home replacement.

Opinion Dynamics conducted a three-year, real-time embedded process evaluation of the Pilot. The evaluation objectives were to better understand energy and non-energy impacts, project costs, barriers to participation, and key elements of a successful program design. The evaluation team used information from Pilot documents, Pilot team meetings, home inspection results, and interviews with six stakeholders and 29 manufactured home residents or homeowners (referred to as participants).[1]

## 1.2 Key Findings

Key findings from the evaluation include:

- **Existing, pre-1994 manufactured homes are generally in poor condition and in need of major repairs.** Issues related to the foundation, floor, roof, walls, plumbing, and HVAC systems. Mold and pests, as well as air and water leaks, were common.
- **Participants actively worried about their home.** Participants were stressed about affording rent and their utility bills and faced evictions or shutoffs. Many participants reported being uncomfortable in

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[1] Earth Advantage representatives were not interviewed, while a representative of Saint Vincent de Paul of Lane County, a park operator, was interviewed.

their homes and feared it would burn down due to electrical issues and poor wiring. Close to half of the existing manufactured home residents (11 of 25) mentioned new health conditions occurring or prior health conditions worsening as a result of the problematic home conditions. Residents frequently mentioned itchy or watery eyes and coughs.

- **Participants learned about the Pilot through Pilot staff, their park operator, or through a manufactured home retailer.** The majority of participants (72%) were excited to learn about the Pilot, though 28% were unsure or skeptical if the opportunity was a good fit for them. Low-income households tend to be conservative with new financial endeavors and are cautious about taking on new debt; for these reasons, some lost interest after learning more about the financial commitment required from them.
- **Some homeowners who have pursued home replacement through the Pilot have been unable to piece together sufficient funding (incentives and subsidies) to make a loan financially viable for them.** No participant has yet qualified for the United States Department of Agriculture (USDA) Rural Housing Service Section 502 low-interest loan or Craft3's loan. One participant has thus far qualified for UCAN's weatherization subsidy. Most homeowners on private land (3 of 4) were able to leverage the equity in another piece of property (home or land) to get cash for a down payment on their new mobile home.
- **Oregon Housing and Community Services (OHCS) weatherization funds funneled through Community Action Agencies are an important subsidy that reduces the amount of money the homeowner will need to borrow on the loan, but are limited in their availability.** Currently, each CAP agency chooses whether they will request permission to allocate weatherization funds to manufactured home replacement and one has agreed to support the Pilot. This means additional work for Pilot staff to engage each agency and limited availability of these funds for participants.
- **Project costs can vary and are hard to predict** but have so far ranged between $75,000 to $123,000 for single wide replacements. If asbestos is found in the existing home, it can add up to $10,000 to the decommissioning costs. The site preparation phase can incur additional costs if the ground needs to be leveled and reinforced. If the new home does not come with gutters, those must be hung along with adding stairs or a ramp to the front door. Difficulty estimating project costs increases the difficulty for a participant to convey to a lender what they need to borrow.
- **There were some challenges with selecting a new manufactured home that will fit on the existing property.** Newer homes tend to be larger than older homes, which can make it difficult to comply with setback requirements when siting a home in the same lot. Park operator participants visited multiple retailers to find appropriately-sized homes.
- **Our assessment to date indicates that participants realize substantial non-energy benefits after moving from a pre-1994 manufactured home to a new, efficient one.** The biggest difference noted by participants was improved thermal comfort. They no longer needed extra blankets and jackets to stay warm. Most reported health improvements due to improved air quality in the new home. They also worried less about things in the new home, and one felt much safer in their new home and had an easier time getting around in their wheelchair and walker.
- **The Energy Trust incentive influenced park operators to replace their old inefficient manufactured homes and eased the process for private land homeowners.** For one park operator, the incentive allowed them to replace more homes than they would have otherwise. Two private land homeowners felt more comfortable in their decision to buy the home, knowing that they had additional funds to help with removing the old home and preparing the site.
- **Additional resources and partnerships should allow the Pilot to expand to other areas of Oregon.** Energy Trust has been working with OHCS to increase the availability of funding for home replacement throughout the State of Oregon. The 2019 passage of Oregon House Bill 2896 will allocate funds for

decommissioning of old homes and for loans to households to buy new manufactured homes. Interviewed Pilot partners and park operators all want to pursue replacements in other parks they manage in Oregon.

## 1.3 Conclusions and Recommendations

We offer the following conclusions and recommendations.

**Conclusion 1:** There is a considerable need to replace pre-1994 manufactured homes in Oregon. Many of these homes are in disrepair. Roof leaks, cracks in the walls, holes in the floor, mold, and pests make the homes uncomfortable, worrisome, and potentially unhealthy to live in.

**Conclusion 2:** The Pilot is sufficiently resourced, attractive, and flexible enough to encourage manufactured home replacements inside and outside of the park context. Pilot staff have engaged stakeholders to facilitate replacements for residents in parks indiscriminate of whether the participants own the home, land, or neither. Pilot partners support homeowners who do and do not own their land and also engage park operators for replacements where tenants occupy the homes.

**Conclusion 3:** Each replacement project is unique due to the household's financial situation and the land plot the home is sited on. Each homeowner considers their assets and whether a loan is in their best interest. At the same time, loan decisions are complicated when project costs are hard to estimate. The cost to replace a single wide manufactured home can vary considerably, and some of the costs are hard to predict. Individualized attention is necessary when home replacement projects occur on a case by case basis.

> **Recommendation:** Pilot staff should ensure continued or reinvigorated discussions with interested partner organizations and initiate discussions with other potential organizations to secure funding for a participant liaison role that can provide individualized support and be a point of contact to shepherd the participant.

**Conclusion 4:** The Pilot brings together a variety of financial support, including incentives, subsidies, grants, and low-interest loans, but most participants cannot qualify for all of them, and some have had difficulty qualifying for any. Most of the Pilot's financial support is available in geographically restricted areas, and only one of the state's 15 CAP agencies contributes weatherization funds to the Pilot. Soon, Oregon House Bill 2896 will provide additional funds for manufactured home replacement, which can potentially be used to supplement Pilot support.

> **Recommendation:** Pilot staff should investigate ways to make best use of the HB2896 funds and determine opportunities for combining them with Pilot funds to further reduce the cost of home replacements for participants. Pilot staff should also pursue the possibility of OHCS approving all of Oregon's CAP agencies to assign a portion of weatherization funds to manufactured home replacement.

**Conclusion 5:** Early post-occupancy findings point to substantial non-energy benefits for people who move from a pre-1994 manufactured home to a new, energy-efficient one. Thermal comfort was markedly improved, health conditions improved, and residents reported reduced stress and worry in the new homes. Some experienced pride in the new home and increased feelings of safety as well.

> **Recommendation:** Subsequent evaluations should include efforts to measure self-reported non-energy benefits.

# Memo

**To:** Board of Directors

**From:** Phil Degens, Evaluation Manager
Mark Wyman, Sr. Program Manager -- Residential Portfolio

**Date:** September 16, 2020

The pilot has successfully achieved many of its stated goals. The pilot diligently documented the process of replacing an existing manufactured home. The steps needed as well as the cost and time requirements or each step were also gathered. This information is now available to better plan additional engagements and inform current and future partnering organizations and participants. The many non-energy benefits that come as a result of home replacement have also been reported on. These additional benefits show that the pilot does much more than just save energy and are an important factor in gaining support for this type of offering.

In May of 2020 the PUC authorizing additional expenditures to support the ongoing research objectives of the Manufactured Home Replacement Pilot. This also marked the pilot's transition to focus on serving owner-occupied replacement projects. The successful completions during this first phase were exclusively homes purchased by park operators for use as rental housing. We expect significant differences in the financial models and requirements as well as the home occupant experience with the shift from park operator and tenant to owner occupants.

Energy Trust's program team have worked with SVDP to address work quality issues identified in this report. Pilot site inspection information is passed on to facilitate any repair work needed from the manufacturer. Additionally, our partners at Multnomah County's Weatherization Assistance Program identified an issue with the ventilation strategy that has since been remediated.

The forthcoming OHCS program authorized under HB2896 represents an opportunity to address many of the barriers that remain for owner-occupied replacement projects sited in parks. The additional grants and enhanced financing terms expected from the HB2896 program will make home replacement feasible for many more households. Staff are working to support OHCS, sharing the successes of and challenges to our efforts to date, many of which have been documented in this report. Staff are also working with stakeholders to anticipate remaining gaps in the program model.

During the pilot Energy Trust and our partners have managed to provide personalized engagement and support to participants. There is general agreement that when the pilot is scaled up to a larger program is a dedicated team of program liaisons will be required. A scaled up Manufactured Home Replacement (MHR) program has the potential to achieve substantial energy savings among rural, low income and/or minority households. MHR's value to ratepayers and alignment with Energy Trust's mission provides grounds to consider Energy Trust funding of a "navigator" service as an integrated component of our broader program infrastructure and expanding work with community-based organizations throughout Oregon.

We need to acknowledge that the recent natural disasters that have hit Oregon in the form of flooding and wildfires have had a significant impact on many manufactured home communities. The disasters' impacts have increased interest in tapping into the pilot's services and learnings. The most recent news indicates that the impacted communities' needs far exceed the pilot's current resources and many of these needs go far beyond the scope of the pilot research objectives. Many of the learnings and experiences gained from this pilot will support any future initiatives that target the impacted communities

# 2. Introduction and Methods

This document presents findings from a three-year real-time embedded evaluation of Energy Trust of Oregon's (Energy Trust) Manufactured Home Replacement Pilot. The Pilot seeks to retire aging manufactured homes and replace them with new, energy-efficient manufactured homes that exceed code minimum. This chapter introduces the context of manufactured homes in Oregon, the Manufactured Home Replacement Pilot, and the evaluation activities.

## 2.1 Introduction to Manufactured Homes in Oregon

Manufactured homes are an affordable housing option for low- and moderate-income households. Oregon has over 170,000 manufactured homes, which represents about 11% percent of its total housing stock. About half of those predate 1976, when the first Housing and Urban Development (HUD) code established minimum energy efficiency requirements for manufactured homes.[2,3] The energy efficiency elements of the HUD code were last updated in 1994; the first update since its inception.[4] Manufactured homes constructed prior to 1994 tend to have been built with poor quality construction materials.[5] They have less insulation in the walls, ceiling, and floors, with air leakage around doors and windows, and inefficient heating systems. The energy costs per square foot in these older manufactured homes are nearly twice that for residents in similarly aged site-built homes.[6]

Performing energy efficiency retrofits on older manufactured homes is not always feasible or practical. It is difficult to increase insulation levels due to lack of space in the narrow walls, crawl spaces, and attics. Some manufactured home conditions are so poor, they cannot be air sealed properly. And, in some cases, the cost of weatherizing and retrofitting a manufactured home exceeds the value of the home. Further, given the limited funds available for weatherization services, the waiting lists for services that can be years-long.

These limitations of efficiency retrofits, combined with deteriorating and potentially unsafe home conditions, make home replacement an attractive path. In addition to improved energy value, home replacement also enables the homeowner to build their assets because the new manufactured home has a higher value than the older manufactured homes.[7] The manufactured home replacement may also help with park revitalization and park preservation, which contributes to housing stability for low-income families.

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[2] Oregon Housing and Community Services. 2017. “Manufactured Housing: Challenges and Opportunities.” Presentation to the Oregon Housing Stability Council by Dan Elliot on March 3. https://www.oregon.gov/ohcs/OSHC/docs/HSC-2017/1%20-%20Jan%2C%20Feb%2C%20Mar/030317_HSC_Manufactured-Housing.pdf

[3] Talbot, Jacob. 2012. “Mobilizing Energy Efficiency in the Manufactured Housing Sector.” *American Council for an Energy Efficient Economy*. Report Number A124. https://www.aceee.org/sites/default/files/publications/researchreports/a124.pdf

[4] Talbot, Jacob. 2012. “Mobilizing Energy Efficiency in the Manufactured Housing Sector.” *American Council for an Energy Efficient Economy*. Report Number A124. https://www.aceee.org/sites/default/files/publications/researchreports/a124.pdf

[5] Furman, Matthew. 2014. “Eradicating Substandard Manufactured Homes: Replacement Programs as a Strategy. *Joint Center for Housing Studies of Harvard University*. https://www.jchs.harvard.edu//research-areas/working-papers/eradicating-substandard-manufactured-homes-replacement-programs

[6] US Energy Information Administration. 2008. “2005 residential Energy Consumption Survey.” Washington, D.C. US Department of Energy. http://www.eia.doe.gov/emeu/recs/contents.html

[7] Furman, Matthew. 2014. “Eradicating Substandard Manufactured Homes: Replacement Programs as a Strategy. *Joint Center for Housing Studies of Harvard University*. https://www.jchs.harvard.edu//research-areas/working-papers/eradicating-substandard-manufactured-homes-replacement-programs

## 2.2 Pilot Overview

Energy Trust's Manufactured Home Replacement Pilot began in June of 2017. The goals of the Pilot are to:

- refine understanding of savings and costs,
- document non-energy benefits, and
- establish a replicable partnership model between ratepayer-funded programs, housing organizations, and funders.

Staff from partner organizations noted their reasons for participating in the Pilot were primarily to improve the quality of life among the residents that they work with and as one partner noted: "to build a replicable, scalable model that will set an example for the City of Portland and other manufactured home parks."

### 2.2.1 Pilot Management and Partnerships

Given the complexity of manufactured home replacement, the Manufactured Home Replacement Pilot is a collaborative effort among Energy Trust and several Pilot partners or stakeholders. We refer to Energy Trust and CLEAResult as the Pilot staff because they coordinate the other stakeholders, conduct outreach at parks, facilitate the replacement process, and one of the two communicates with every Pilot participant. The other stakeholders in the Pilot include:

- **Earth Advantage** is a partner that conducts home pre-inspections to determine Pilot eligibility regardless of their location.
- **Craft3** is a lending partner that created a loan offering for low-income households who do not own their land to use in the Pilot. They conduct outreach in tandem with Energy Trust, provide financial counseling, and support the participants.
- **UCAN** is another partner, offering funds to qualifying households as a subsidy and has thus far interacted with a subset of Pilot participants.
- **CASA of Oregon**: Arranges financing and provides support to purchase manufactured home parks and establish them as cooperatives in which individual residents own their homes and the residents collectively own the land on which the homes are sited. CASA recruits new participants and provides one on one coordination and support to homeowners in the cooperatively owned parks they have supported throughout Oregon.
- **NeighborWorks Umpqua**: Purchases manufactured home parks and operates them as a nonprofit. Residents own their homes and pay rent to NeighborWorks to lease the land on which they are sited. They have a Homeownership Center that is transitioning into a broader Financial Opportunity Center that will help participants navigate the home replacement process.

CASA and NeighborWorks Umpqua will serve as project managers for replacement projects in their parks, coordinating funds from different sources and supporting participants throughout the replacement process. They also oversee infrastructure improvements in the parks they purchase and provide homeownership counseling services for the residents.

### 2.2.2 Incentives and Subsidies

A key goal of the Pilot is to understand the savings and costs of replacing manufactured homes. Initial research by Energy Trust determined the likely energy savings estimates. The estimated savings justified incentives in the range of $7,500 to $15,000 depending on characteristics of the home being replaced and the new, efficient home being installed. Throughout the Pilot, Earth Advantage conducts energy audits of homes prior to replacement, and Energy Trust will use this information along with a billing analysis to estimate energy savings resulting from home replacement.

In addition to Energy Trust's incentives, the Pilot leverages subsidies from a Community Action Agency working in Douglas County: UCAN. UCAN provides weatherization services to low-income households and petitioned OHCS to use a portion of their weatherization funds to support up to five manufactured home replacements. In October 2018, OHCS approved UCAN to provide up to $20,000 as a subsidy to reduce the amount of principal the homeowner needs to borrow on their loan. According to one Pilot staff member, "We wanted to stack the energy savings subsidy with other types of subsidies. The thinking is that you could compress several years of critical interventions… and offer a grant that, paired with a loan, could make this an affordable option."

Program partners described Energy Trust incentives as "one tool in the toolbox" among the many for replacing aging manufactured homes, including grants, financing, and social services. Nonetheless, partners stressed that the incentives are critical tool. One interviewed Pilot partner stated that "Those subsidies are going to make it possible. I cannot express how important that is. I think it is what is going to be the turning point so that people are going to say, 'I can actually do this.'" Partner organization staff reported that Energy Trust incentives not only reduce the cost of replacement for manufactured home residents, but also make replacements more attractive to potential lenders.

### 2.2.3 Financing

While the Pilot seeks to reduce the cost of manufactured home replacement with Energy Trust incentives and other subsidies, the remaining up-front cost is likely to be substantial. For example, a new ENERGY STAR® single-wide manufactured home costs a minimum of $50,000, though often more, and retailers reportedly require 50% at the time of purchase. After accounting for the incentive, the homeowner will need to borrow at least $20,000 for the home itself. This upfront cost can be difficult for predominantly low- and moderate-income residents of manufactured home parks. To address this, the Pilot also includes financing options to cover the upfront cost and allow repayment over time.

Pilot staff engaged Craft3, a community development financial institution (CDFI), to develop a loan product to support manufactured home replacements. Craft3 leaned on its experience working with low-income households and designed a product that would yield a monthly payment potentially acceptable to a homeowner earning 50% of the area median income. Craft3 commented that they sought to design a loan that is fair, equitable, and "a stabilizing force for the communities we're trying to serve."

Another loan option available to Pilot participants is the USDA Section 502 Direct Loan Program, which offers income-qualified residents of rural areas loans with payment assistance subsidies that can reduce interest rates to as low as 1%. Other jurisdictions have used these types of loans to support manufactured home purchases in cooperatively owned parks, and Pilot staff and partners expect nonprofit-owned parks to be eligible.

### 2.2.4 Participants

Pilot participants' homes are located in one of three settings:

1. A non-profit park operator owns the land and purchases homes for use as rentals. An example is the Oakleaf Park owned by Saint Vincent de Paul (see below for more information). We refer to the households in this setting as "residents" because they do not own the land or home.

2. A resident-owned park (also called a cooperative) where residents own their home and lease the land. An example is the Umpqua Ranch park, supported by CASA. We refer to these households as homeowners in a park.
3. An individual manufactured homeowner on private land (outside a park). We refer to these households as homeowners on private land.

Energy Trust's lending partners will issue loans to qualified households seeking to purchase a manufactured home (setting 2 and 3) and to not-for-profit park owners to purchase homes for use as an affordable housing rental (setting 1). Most of the manufactured homes replaced through the Pilot so far have been purchased by park operators (setting 1).

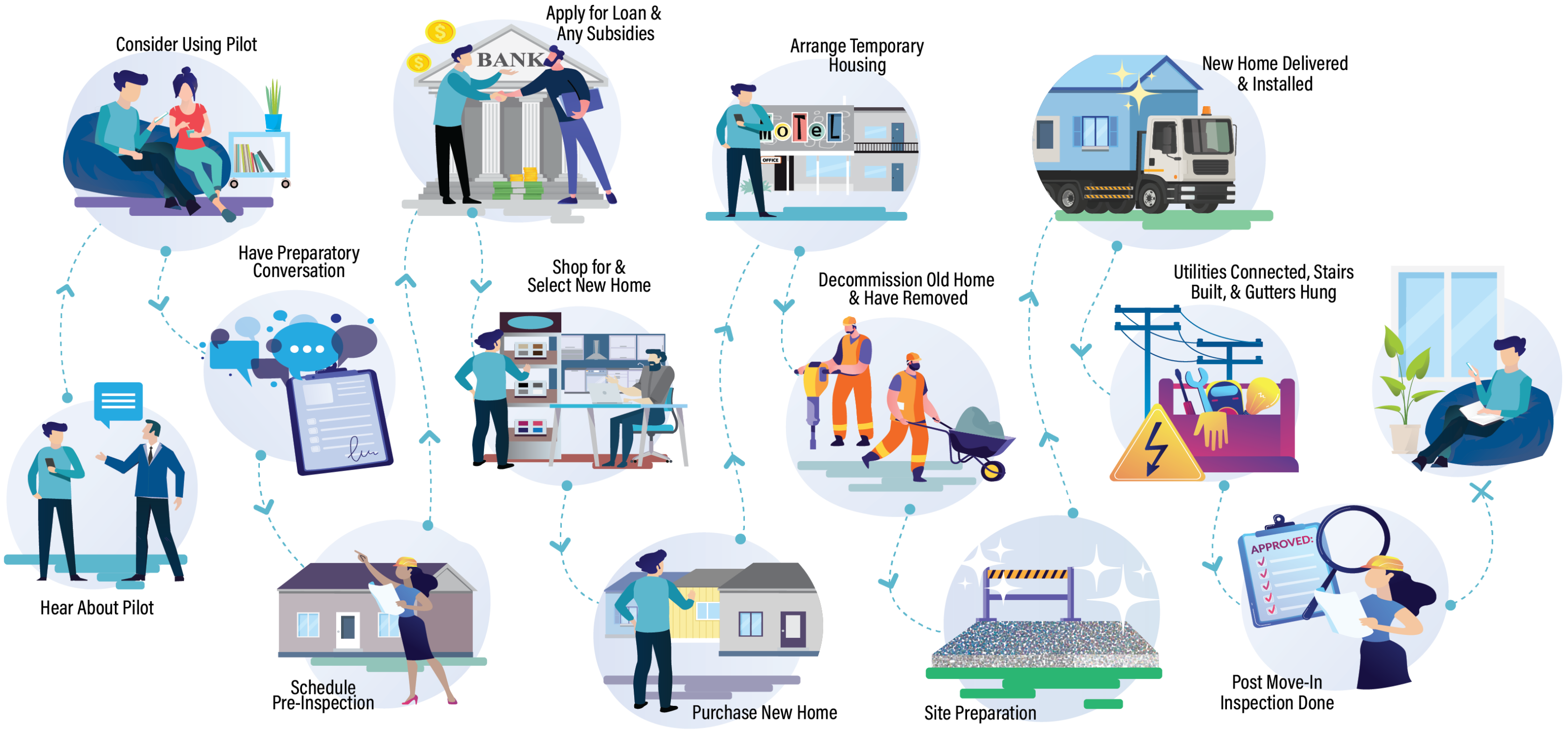
Saint Vincent de Paul of Lane County acquired a distressed park in Portland in 2017. The park was in danger of being sold to a redeveloper, in which case residents would be displaced. The park itself needed to be redeveloped, and the park's manufactured homes were in poor condition. The incentives available through the Energy Trust's Manufactured Home Replacement Pilot made it feasible for Saint Vincent de Paul to plan its redevelopment project and replace the pre-1994 manufactured homes.

Park operators that replace inefficient manufactured homes are making positive impacts by retiring old inefficient homes, but the Pilot's intended primary audience is households interested in replacing their inefficient manufactured home who live in non-profit-owned or cooperatively owned parks. Energy Trust staff noted concern that owners of for-profit, investor-owned parks could sell the land or take advantage of the improved conditions resulting from the Pilot to raise rents, potentially displacing residents who had replaced their homes. Nonpark, private land settings were not initially targeted for the Pilot. Still, staff expanded participation to households interested in replacing their manufactured who live on their own land outside a park.

The home replacement process involves several steps and can take multiple years (Figure 1). After learning about the replacement opportunity and the financial requirements, they need to consider if it is a good fit for them. If they determine it is, they schedule a home pre-inspection to see if their existing home qualifies. They apply for a combination of incentive, subsidy, and/or loan. If they acquire enough funds to make the home replacement feasible, they move forward with the purchase of a new qualifying manufactured home, find temporary housing (with assistance from the Pilot), have their existing home decommissioned, have the site prepped for the new home, and have the new home installed. After moving into the new home, they have another inspection, and then receive their incentive funds.

Figure 1 presents the key steps a participating household takes through the Pilot to replace their home.

Figure 1. Participant Journey



The participant journey begins by hearing about the Pilot and considering whether to participate. Then, the household has a "preparatory conversation" with a Pilot representative or Craft3 to assess whether the opportunity is right for that household. They may determine it is not the right time and can go back to considering whether to use the program. If the outcome of the conversation is such that they proceed, they then schedule a home pre-inspection to see if they qualify for the Energy Trust incentive. If they are ineligible, they cannot participate in the Pilot. If they are eligible, they proceed by applying for a loan or any other subsidies available. They shop for and select the new, efficient manufactured home. They purchase the new home and arrange for temporary housing while the home is replaced. The old home is decommissioned and removed. The site is prepared for the new home, which may involve leveling the land and pouring a new concrete foundation. Once the site is ready, the new home is delivered and installed. Installation involves connecting the utilities and adding stairs and gutters. The participant can move into their new home now. A Pilot representative conducts a post-move-in inspection, and the customer journey is complete.

## 2.3 Evaluation Methods

The objectives of the embedded process evaluation are to better understand:

- Energy impacts and quality of life improvements,
- project costs,
- barriers to participation, and
- key elements of a successful program design.

To meet the objectives, this evaluation draws from a variety of informational sources, including:

- A review of Pilot documents
- A review of home pre-inspection results
- Notes from Pilot team meetings
- In-depth interviews with Pilot stakeholders (staff and partners)
- Interviews with park operators that replaced homes and residents living at those parks
- Interviews with households who moved into new homes replaced through the Pilot
- Interviews with individuals on private land pursuing Pilot participation

Members of the evaluation team attended Pilot team meetings from 2017 through mid-2019. After mid-2019, evaluation staff checked in with Pilot staff on an as-needed basis.

Evaluation staff interviewed key Pilot stakeholders at two junctures. The first juncture was early in the Pilot period and covered topics such as the goals of the Pilot and anticipated challenges and opportunities. The second set of interviews covered how the Pilot implementation had gone so far; any challenges with recruitment, financing, or replacements; lessons learned; and stakeholder's plans concerning the future of manufactured home replacement in Oregon.

Interviews with potential Pilot participants also occurred at two key junctures: the first occurred soon after the candidate household learned about the Pilot and covered topics such as their reaction to hearing about the opportunity, any concerns they had about the process of replacing their home, and their existing home conditions. We refer to these interviews as "intake interviews" in Table 1. Four of the 29 intake interviews were with homeowners living on privately-owned land, one of whom had already purchased their newly manufactured home. The rest were residents or homeowners in parks. After their intake interview, some of the homeowners decided not to move forward with participation. Therefore, the data from the intake interviews characterizes the situations of households in manufactured homes, which represents participants and nonparticipants.

The second participant interview occurred after they moved into a new manufactured home purchased with support from the Pilot. We refer to these as "post-move in" interviews. All five post-move in interviews were conducted with residents living in homes purchased by park operators because no homeowner participant had yet completed a manufactured home replacement at the time of the post-move in interviews.

Evaluation team members conducted the first intake interviews early in the Pilot in-person at Saint Vincent de Paul's Oakleaf park and Pilot partner staff interviewed potential participants in-person at the CASA-owned Umpqua Ranch park. Evaluation team members conducted the 2019 and 2020 intake and post-move in interviews over the phone. Five of the Oakleaf residents participated in both an intake and post-move-in interview, for a total of 29 participant interviews.

Table 1. Evaluation Interviews

| Type of Interviewee | Timeframe | Number Completed |
|---|---|---|
| Participant intake interview | 2017 or 2018 | 24 |
| Participant intake interview | 2019 or 2020 | 5 |
| Participant post-move in interview | 2019 or 2020 | 5 |
| Pilot staff or partner (stakeholder) | 2017 | 4 |
| Pilot staff or partner (stakeholder) | 2020 | 6 |

Interview instruments for these groups may be found in Appendix C.

# 3. Findings

This chapter presents the evaluation findings beginning with a description of the manufactured homes that participants (residents in parks and homeowners in parks and on private land) occupied along with their worries in those homes. Then we discuss outreach, considerations for participation, and the Pilot's financial support. Section 3.4 reviews the steps in the replacement process, the replacements to date, and the Pilot's influence on the replacements. Next, we present findings from residents who moved into a new manufactured home incented through the Pilot. We end the chapter with a review of stakeholder collaboration and the future for manufactured home replacement in Oregon.

Demographic data for the interviewed homeowner participants and park residents is in Appendix B.

## 3.1 Existing Home and Health Conditions

### 3.1.1 Prior Home Conditions

**Interviewed residents at the Oakleaf and Umpqua Ranch parks described their existing manufactured homes as being in a livable condition at best, with many rating them as less than comfortable.** Half of them describe the overall condition of their home as "fair" or "livable," while the other half said their home is in a "bad" or "poor" condition (Figure 2). Other ways they described their home included, cold, drafty, small, and horrible (Figure 3). One participant on private land described their house this way:

> *It's a 1971 home. There's no insulation in that thing. It's horrible. It's so cold and everything leaks. Around the windows it leaks. So, the cost to keep it warm during the winter and cool in the summer is substantial.*

Figure 2. Description of Current Home (n=29)

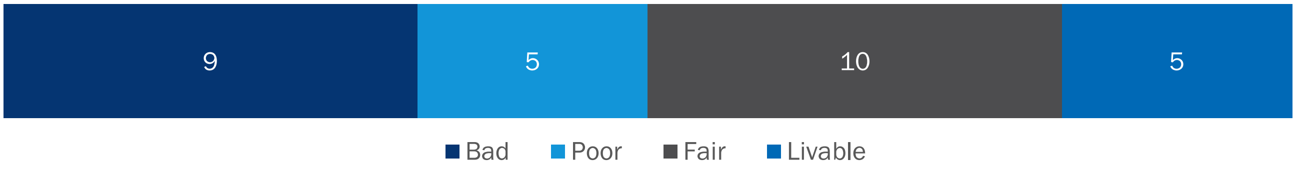


Figure 3. Participant Words Used to Describe Current Home Condition (n=29) [a]

[a] Multiple responses allowed.

**All of the homes were in need of repairs** with most households (83%) reporting they needed two or more repairs.[8] Two respondents stated their home was in horrible shape and should be torn down completely. The most common repairs they needed related to their foundation, roof, or windows (19 of 25; Table 2). Respondents described structural problems and said their homes were off-balance, tilting, or sliding. Others said there were holes in their floor and that soft spots or creaking floors let them know it was compromised. One person shared that they commonly have mushroom growth in floor cracks, and another said their child treated the mice as “pets.”

Envelope concerns were also common (22 of 29), which included window or roof leaks, lack of insulation, and drafts. Some cracks in the walls around doors were so large you could see through them. More than half of respondents (16 of 28) also reported that their home is leaky when it rains. Many households are dealing with harsh consequences from water intrusion, including but not limited to mildew and mold growth, and rotting walls and floors. One resident had “buckets all over the place” to catch incoming rainwater, and another reported large areas of their homes overtaken by black mold. Plumbing concerns related to leaking pipes, and one woman said her piping was so “broken up” that she used a hose to meet her water needs. One respondent noted their problem with mice is so severe they are unable to put anything in cupboards unless it is sealed in plastic containers.

Table 2. Needed Home Repairs (n=25) [a]

| Needed Home Repairs | Number of Respondents |
|---|---|
| Foundation | 10 |
| Roof | 10 |
| Doors or windows | 10 |
| Plumbing | 6 |
| Insulation | 6 |
| HVAC | 4 |
| Mold or pests (e.g., mice) | 3 |

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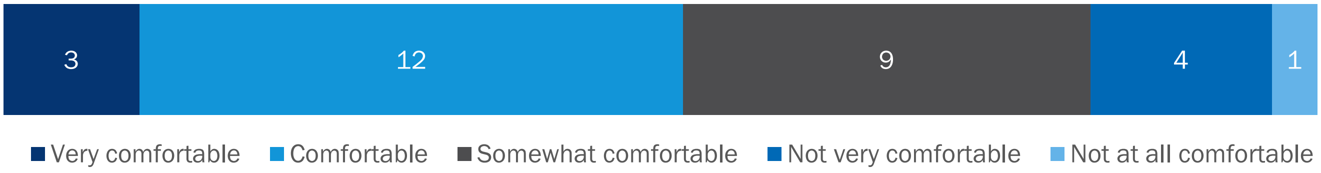
[8] All but one (24 of 25) participant reported their home needs some type of repair with the last participant mentioning they had just completed major repairs.

| Needed Home Repairs | Number of Respondents |
|---|---|
| Electrical (e.g., wiring) | 2 |
| Other | 7 |

[a] Multiple responses allowed.

**Nearly half (14 of 29) also reported being less than comfortable in their home** (Figure 4). More than half used electric space heaters as supplementary heating (16 of 27; 59%) to stay warm. Of those, about half (7 of 13) said they used them all the time when it is cool out. One mentioned they leave the oven on and open for additional heat. Wood stoves were another heating method interviewed households used; 6 of the 11 Umpqua Ranch residents had wood stoves, and so did two of the residents on private land. Homeowners and residents also found their homes uncomfortable in the summer, with it being humid inside. A participant on private land said their existing home "had such outdated heating equipment, you had to leave it on all day, almost 24 hours because it was such an old trailer." Some Oakleaf residents reported being "freezing" in the winter, with one stating they paid $300 per month for their electric bill, and they were "barely" kept warm. Many of the Umpqua Ranch homeowners (6 of 9) reported paying more than $200 for their monthly electric bills in the winter; two of these said they paid up to $350 per month in the winter.

Figure 4. Comfort of Home (n=29) [a]



[a] Multiple responses allowed.

**More than two-thirds of interviewed households (17 of 25; 68%) said they felt unsafe in their home.** Most respondents reported feeling unsafe due to electrical or mold issues (Table 3). Eight respondents expressed fear due to their electrical condition or fire safety in their home. One mentioned using extension cords because many outlets do not work and the age of the electric panel worries them. Another stated, "I'm afraid the thing is going to burn down. I'm constantly worried about it." Respondents who said they felt unsafe due to reported mold growth in various areas, including bathrooms, bedroom closets, ceilings, and windows throughout the home. Both respondents who said they feel unsafe because of security issues in their home stated that their door either was hard to lock or would not properly lock at all. Other reasons respondents said they felt unsafe in their home included the stability of their home during windstorms, water pressure issues, and issues with their heating system or flooring; one household mentioned an area in their home where there is no floor.

Table 3. Reasons Participants Feel Unsafe in Home (n=25) [a]

| Reasons for Feeling Unsafe in Home | Number of Respondents |
|---|---|
| Electrical and fire safety (outlets, wiring) | 8 |
| Mold | 6 |
| Security (door lock issues) | 2 |
| Other | 5 |

[a] Multiple responses allowed.

Earth Advantage staff took pictures of the homes during their pre-inspection audits. Figure 5 shows a hole in the ceiling of one home and mold growth in another.

Figure 5. Poor Conditions in Participant Homes

The main reason preventing more than half of households (13 of 18) from completing repairs in their home is the cost. Other factors preventing repairs include time constraints, foundation issues (e.g., home located on sliding hill), and choosing to not repair because the home will be decommissioned and replaced soon as part of a park redevelopment project.

**Interviewed households actively worried about their home, particularly its poor condition and affordability** (Table 4). Their financial concerns were about affording rent, paying non-utility bills, and their or family member's employment status. Respondents also worried about their home conditions. For two respondents, their biggest worry in their home involved the roof. One shared that his roof is currently sagging, and "when the wind blows, we're afraid that something may come down on us." Many also worried about energy-related concerns, which involved staying warm enough, paying energy bills, and fear of utilities being shut off. A few noted that they had worried about family issues such as divorce or custody of children. Nearly a third of Oakleaf and Umpqua Ranch households also reported the current park-led replacement project as a worry for them in the last 30 days.

Table 4. Issues Creating Worry or Stress for Participants in Last 30 Days (n=26) [a]

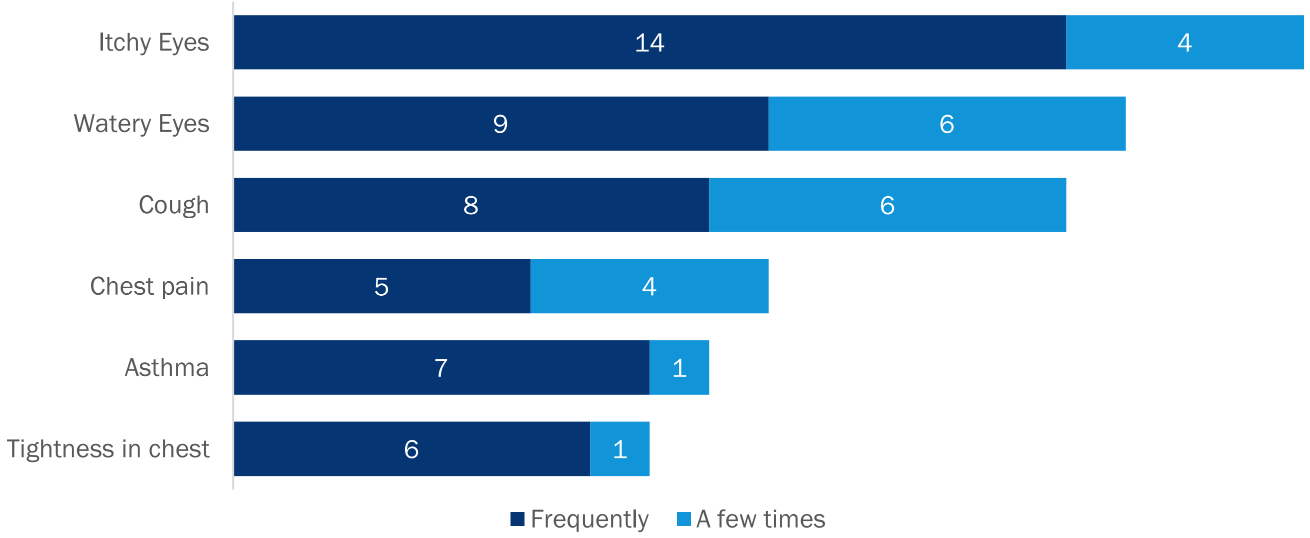
| Participant Worries | Number of Respondents |
|---|---|
| Financial (eviction, employment status) | 9 |
| Home conditions | 8 |
| Park revitalization project | 8 |
| Energy-related (energy bills, utilities being shut off) | 5 |
| Family issues | 3 |
| Health due to home conditions (mold, pests) | 3 |

[a] Multiple responses allowed.

### 3.1.2 Prior Health Conditions

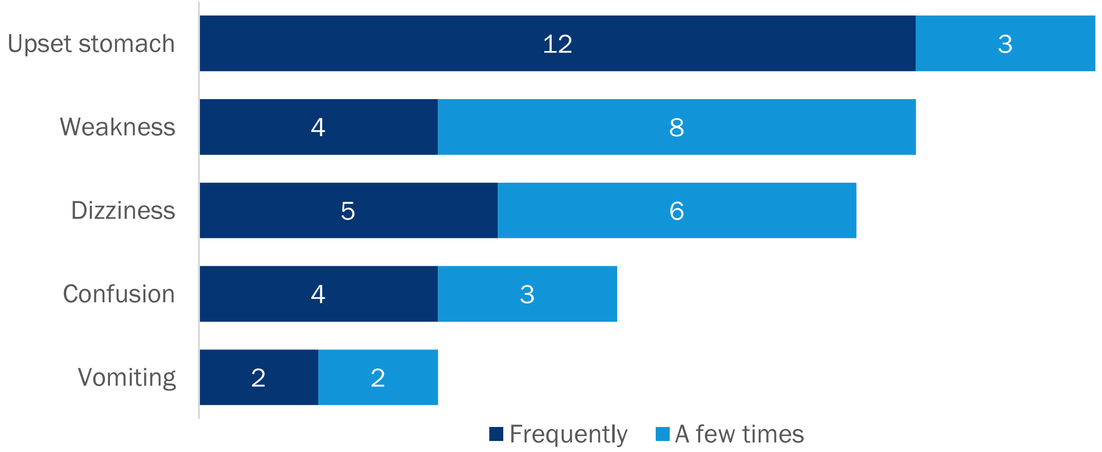
Interviewed Oakleaf and Umpqua Ranch residents commonly reported that they or someone in their household experienced health conditions related to the air quality in their house (Figure 6). Itchy and watery eyes were common, along with cough. Nearly half of the households interviewed (11 of 25) mentioned new health conditions occurring or prior conditions worsening because of the home conditions described earlier. Respondents reported that their asthma, bronchitis, or allergies were exacerbated in the homes. One respondent who had itchy, watery, and burning eyes all the time said that when their furnace comes on, they have a sneezing spell. One attributed their pneumonia to their leaky home and mold. Another said that their wife's breathing and heart condition were worse due to the mold and mice because she works from home and is home all day.

Figure 6. Health Conditions in Households Related to Air Quality (n=25)



About half of the respondents also reported experiencing upset stomachs frequently with nausea and diarrhea (Figure 7). Others mentioned headaches and lethargy.

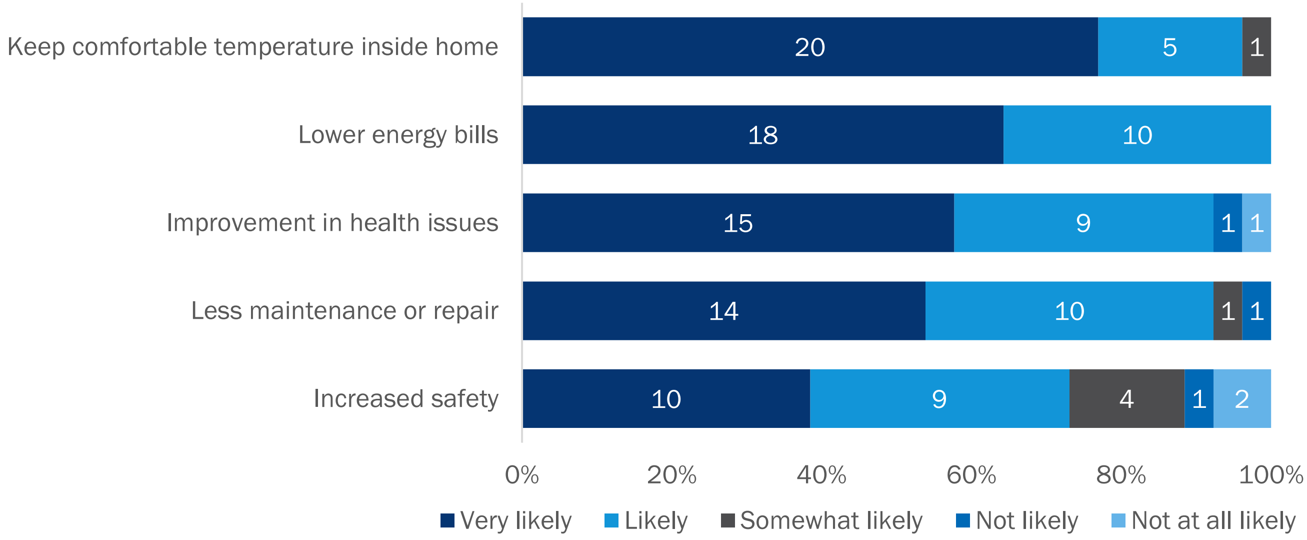
Figure 7. Other Health Conditions in Household (n=25)



### 3.1.3 Benefits Expected

**Potential participants expected improved thermal comfort and energy savings to be the most likely benefits of replacing their homes** (Figure 8). Respondents could easily envision how a new home would be warmer in the winter and cooler in the summer and how they could save on energy bills. Nearly all participants (24 of 26) said health improvements would be likely as well. While participants rated safety improvements to be the least likely benefit, still, nearly three-fourths (73%) said improvements in safety would be likely if they moved from an older manufactured home to a new one.

Figure 8. Expected Likelihood of Benefits from New Manufactured Home (n=29)



## 3.2 Participant Outreach

### 3.2.1 Stakeholder Outreach at Parks

Pilot staff conduct outreach in two primary ways depending on the park's ownership structure. At parks where a non-profit organization owns the land, Pilot staff approach and engage the non-profit group. Examples of this method include Saint Vincent de Paul at the Oakleaf park and NeighborWorks Umpqua at the Newton Creek park. In these parks, the non-profits coordinate the home inspections, acquire funding and financing, select new homes, support residents with temporary housing if needed, and oversee the site decommissioning, preparation, and installation.

The Pilot's second outreach method is to identify a cooperatively owned park that would be a good fit for the Pilot and engage the residents there. The Pilot partner, CASA, is often a conduit between Energy Trust and these types of parks. The Pilot staff present the opportunity to all interested individuals at the park. Those who want to learn more and pursue replacement hold conversations with Pilot staff or partners. These conversations, which an interviewed Pilot partner referred to as "preparatory conversations," are an important part of the Pilot's education and outreach strategy. In these conversations, the potential participant learns about the Pilot support available to them – financial and otherwise – and learns the commitment required from them to participate. Craft3 reported having held about 25 of these preparatory conversations by May of 2020.

These conversations embody responsible lending and help fulfill the Pilot's goal that participation leads to improved quality of life for participants. The Pilot staff help the potential participant think through what their budget is, what their expenses are, and how they would feel about paying the monthly loan amount. The Craft3 representative explained that they discuss topics other lenders may not ask about and that they hold these conversations before the homeowner fills out an application (whereas a traditional lender would require an application and fees beforehand). If the homeowner feels they are not ready to move forward with a loan, Craft3 or Pilot staff will connect the homeowner with the right resources to prepare them to acquire new debt and be in a position to afford the additional monthly payment.

### 3.2.2 Home Manufacturer Outreach

In 2018, Pilot staff approached some retailers to learn about key aspects of manufactured home replacement. They asked about typical deposit requirements, timelines for backorders, how transport is handled, available grants, and working with third-party lenders. Engaging retailers was not intended to be a primary outreach approach for the Pilot. Between participants and Pilot staff visiting manufactured home retailers in Oregon, the following retailers learned about Energy Trust's Pilot: Cascade Factory Homes, Clayton Homes, Crown Manufactured Homes, Factory Expo Home Centers, J&M Homes, Palm Harbor Mobile Homes, and Willamette Homes.

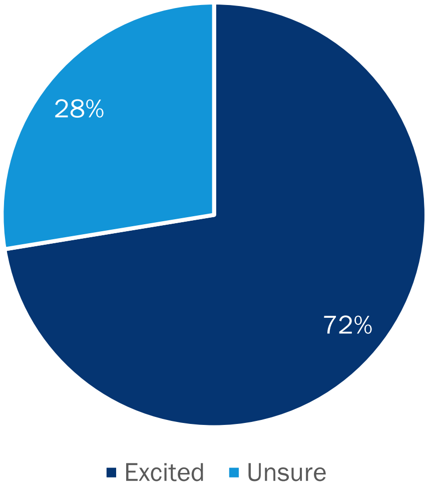
Four participants seeking to replace their manufactured homes on privately owned land first learned about the Pilot through a home retailer/manufacturer. These participants visited a J&M Homes showroom to shop for a new manufactured home, and a sales representative told them about the Energy Trust incentive. Two voluntarily reported that the salesperson was very helpful with information.

Many ratepayer-funded, residential energy efficiency programs benefit from midstream retailer-level engagement to spread program awareness. The Manufactured Home Replacement Pilot could similarly benefit from engaging manufactured home salespersons to inform potential homebuyers about the incentive and encourage them to purchase a qualifying, efficient home model.

### 3.2.3 Participant Considerations for Participation

**Interviewees had positive expectations and the majority were excited to hear about the Pilot opportunity, though some were unsure or skeptical** (Figure 9). Those who were excited were looking forward to participating because they had older homes in need of repairs, and it appeared to them that the program would resolve those needs. Some respondents said the program would open possibilities for them, and one said it "would make my dream come true" to have a new home and not need to perform maintenance regularly. Those who were unsure or skeptical questioned the impetus behind the Pilot, wondered if they could afford to participate, or were just unsure about whether the Pilot support would come to fruition.

Figure 9. Reactions Upon Hearing about Pilot (n=29)



Interviewed stakeholders described similar reactions from potential participants upon hearing about the Pilot. They characterized three types of participant reactions:

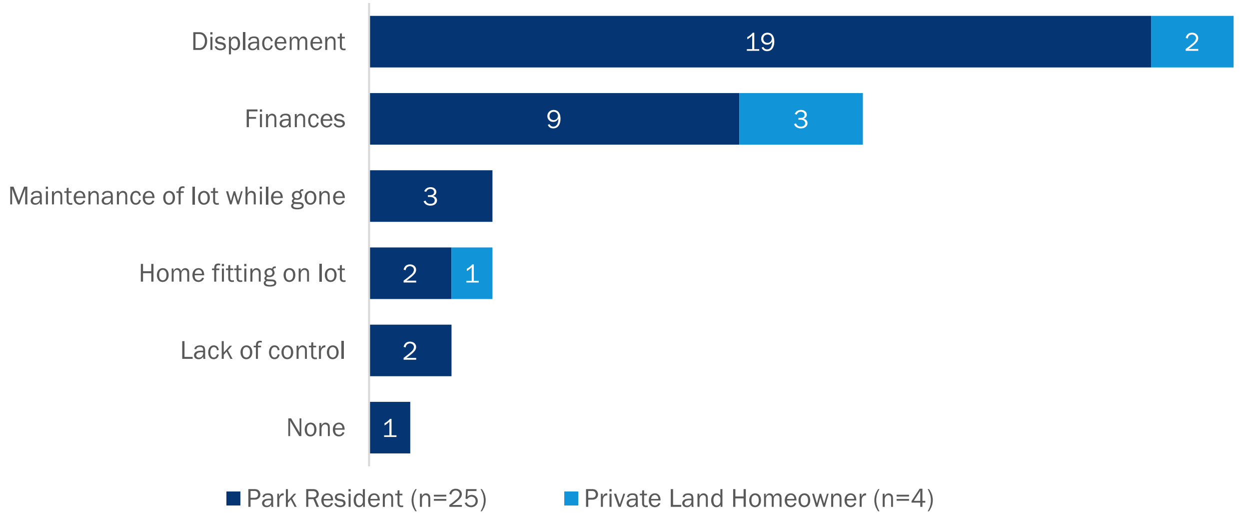
1. Those that feel the opportunity is achievable within their means and are excited to make it happen.
2. Those that are excited, but wary and want to see a successful example before doing it themselves.
3. Those that do not feel they would qualify for a loan or do not want to take on additional monthly payments.

**Some low-income persons are averse to debt or mistrust people offering free or cheap money.** Stakeholders reflected on their early conversations with households and said a lesson they learned was that "free money" was not as attractive as it seemed on paper. After having preparatory conversations and the potential participants learned that they would pay for the home over time via a debt, many reportedly lost interest. Some were retired folks uninterested in taking on debt at their age. Others seemed to mistrust or be skeptical of the opportunity. Low-income populations are targets for predatory lending, and they have learned to be suspicious of deals offering free or cheap money. They tend to be cautious, act conservatively, and think carefully before moving forward with large financial decisions. As the CASA representative explained, "They may feel they're not in a good financial position to move forward, despite what project partners say, so they will hesitate." Stakeholders sensed that their mindset might change after they see someone like them successfully take advantage of the Pilot offer.

**Both park residents and private land homeowners had concerns about the process of replacing their current home, which for both largely included being displaced and financial costs** (Figure 7). Most interviewees (21 of 29) expressed concern over being displaced, including having to pack all their belongings, finding a place to store them while they waited for the new home, and then fitting their items into the new space. Many also expressed concern over having to find and live in interim housing while they wait for their new home to be ready, and the amount of time it would take, which they noted would be about three months. Two interviewees specifically identified their concern over finding suitable and safe interim housing for their children and pets. Park residents and homeowners (12) were also concerned about finances, including costs associated with the move itself, getting rid of the old home, and inspections. One interviewee also noted they were concerned about the potential impact on their credit.

Interviewed participants also noted additional concerns such as the home fitting on the smaller size of the lot (3) and the extent to which the lot, including their plants and landscaping, would be maintained while they were gone (3). Two other interviewees noted that the biggest difficulty to the move would be the lack of control over the process. One interviewee (out of 29) indicated they had no concerns with home replacement.

Figure 10. Concerns with Home Replacement (n=29)



**In their intake interviews, two homeowner households mentioned they considered moving to a site-built single-family home instead of replacing their manufactured home.** One said that the lowest cost for a site-built house was $125,000, which was unaffordable for them. The other lived in a park where she rented the land plot but owned the house. She said that the increasing rental prices at the park combined with a mortgage on a manufactured home were similar enough to the costs of a site-built house that she chose to sell her manufactured home and purchase a single-family home. She reported, “the last time we were down looking at it, we were talking about all the numbers and stuff with the dealer, and on the way home, I was like uh, what? $725 dollars a month lot rent, plus the mortgage on that; that’s enough for the mortgage on the new house where we own the property too. So, that made more sense to me.”

**Increasing interest after the first replacement seems to be just what happened at the participating parks.** As soon as the four new units were delivered and while they were being installed at Newton Creek, the NeighborWorks Umpqua management received phone calls from residents asking how they could also get a new unit. Similarly, word about the replacement support spread from Saint Vincent de Pauls’ Oakleaf tenants to their Arbor Mobile Home Park residents. The Arbor Mobile Home Park residents contacted Pilot staff, who then began developing an outreach plan for that site. Energy Trust introduced the Pilot opportunity to Arbor residents in collaboration with Living Cully and Multnomah County in late 2019.

## 3.3 Financial Support

This section reviews the Pilot’s financial support available to homeowner participants and challenges participants have had qualifying for them. It ends with a brief review of the funding and financing that park operators received to replace homes through the Pilot.

### 3.3.1 Financial Support for Homeowner Participants

One of the Pilot's defining features is the package of financial support it can offer potential participants (Table 5). Energy Trust's incentive and the UCAN's subsidy can be used to reduce the amount of principal a homeowner needs to borrow on their loan, thus reducing the monthly payment to a point where it is affordable.

Table 5. Financial Support Available through the Pilot to Homeowners

| Organizational Source | Form of Funds | Maximum Amount |
|---|---|---|
| Energy Trust | Incentive | $15,000 [a] |
| UCAN | Subsidy | $20,000 |
| Craft3 | Loan | Project-specific |
| USDA Rural Housing Service | Loan | Project-specific |

[a] This incentive amount is for pre-1976, single-wide, electrically heated homes east of the cascades. See Appendix A for Energy Trust incentives for homes built after 1976, double-wide, and gas-heated homes.

The qualification parameters differ for each source of funds, and each has its own terms and conditions. We describe each source of funds in detail:

- **Energy Trust incentive**: Energy Trust has two forms the participant must complete, one each for pre- and post-replacement stages. The potential participant must live in Energy Trust territory and schedule a home pre-inspection to determine eligibility and potential incentive amount. The incentive varies depending on whether the home is heated by natural gas or electricity, whether it was built before or after 1976, and whether the home is east or west of the Cascade mountains (See Appendix A). The participant completes the incentive reservation form to reserve their incentive. Eight incentives had been reserved as of September 2019. Upon completing the home replacement, Pilot partner staff perform a post-siting inspection to ensure Pilot requirements have been met. The participant completes the second Energy Trust incentive form to receive their incentive payment. Energy Trust is looking into whether they can provide the incentive at the time of home purchase so that the homeowner does not need to borrow that amount on the loan and pay interest on it. Having the incentive available at the time of purchase will better serve the needs of the homeowners.
- **CAP agency, weatherization fund subsidy**: Each of Oregon's 15 Community Action agencies can decide whether they want to support the Pilot and allocate a portion of their weatherization funds to manufactured home replacements. Pilot staff have so far engaged UCAN of Douglas County for this role. To qualify for this subsidy, a participant must live in the CAP agency territory, have an annual income below 200% of the Federal Poverty Level, and their home must be electrically heated. If the participant qualifies, UCAN writes a letter committing the funds. The letter demonstrates assets for the participant, which allows them to reduce the amount of loan they need to borrow. At the time of the interviews in Spring 2020, UCAN had completed one commitment letter.
    - The evaluation findings suggest that the CAP agencies' goals and processes might limit their commitment to the Pilot. One potential reason may be due to the fact that these agencies have a two- to three-year waiting list for weatherization services (according to interview data) and they receive no additional funding to cover costs they incur supporting the Pilot. The interviewed CAP agency representative said the amount of weatherization funds they receive is declining each year and wants to limit the amount of funds going to home replacement so they can still provide their regular weatherization services. Staff at CAP agencies may feel pressured to allocate their modest weatherization funds to families that have been waiting years for their standard services rather than provide substantial funds to one family that has not been waiting.

  - At the same time, UCAN has shown a commitment to collaboration in support of the Pilot. UCAN normally has their staff conduct pre-inspection audits to determine eligibility, but UCAN agreed to accept the audit conducted by Pilot staff. Without this arrangement, the participant would need to schedule two pre-inspection audits: one to qualify for the UCAN subsidy and one to qualify for the Energy Trust incentive. This collaboration helps streamline and simplify the participant journey.
- **USDA Section 502 Direct Loan Program**: Income-eligible potential participants in rural areas living in cooperatively owned parks can qualify for this loan with interest rates as low as 1% for 30 years. This low-interest loan offers favorable terms that are not offered by most private lenders. Pilot staff and partners noted that, while the USDA loan product is attractive, the program requirements and process of receiving a loan can be time-consuming and can delay progress. For example, in one participating park, upgrades to the system providing fresh well water were necessary before residents could move ahead with USDA 502 loans. No participants had received one of these Section 502 loans at the times of the interviews in 2020.
  - Interviewed stakeholders also described the program as bureaucratically opaque in its qualification criteria. Pilot staff reportedly directed a handful of residents to apply for the loan, and none of them qualified due to inadequate credit scores. Pilot staff described it as a “defeating moment” for the household when they learned they could not qualify for the low-interest loan—not having the loan terms effectively closed off their path forward to home replacement. The USDA direct loan program does not publish its underwriting criteria, so it is hard to know why the potential participants did not qualify. It appeared to Pilot stakeholders that the qualification criteria are more stringent than the Craft3 loan.
- **Craft3 Loan**: For potential participants outside of rural areas, the Craft3 product is their best option for a low-interest loan. Craft3 has been flexible with their loan offering and adapted it over the course of the Pilot. One advantage is that they do not require a social security number, so they can work with people who have varying immigration statuses if they have an Individual Tax Identification Number. Craft3 also made their loan available to residents in privately-owned parks, whereas previously, it was limited to residents in cooperatively owned parks. As of July 2020, no potential participants had yet completed an application for a Craft3 loan.

**Securing sufficient funding and financing has been one of the larger challenges for interested participants.** It has not been easy for participants to acquire the CAP agency subsidy, and without it, they must borrow even more funds. One participant who did not qualify for the CAP agency subsidy needed an $80,000 loan to cover projects costs, an amount Craft3 did not feel comfortable lending. Participants with fluctuating incomes or “under the table” incomes found it challenging to fill our loan applications and demonstrate credit worthiness.[9] Others had inadequate credit scores, making them ineligible for a loan. One potential participant in conversations with Craft3 was stymied when they could not reasonably estimate the project costs and determine the loan amount they would need (see Section 3.4.1 for more on unpredictable project costs).

The four homeowners on private land who have gotten close to replacing their homes were all able to leverage other equity they had as collateral for financing. Two of them had other homes they owned outright and are taking a mortgage on that home so they have cash for the down payment on the new manufactured home. Another is using the equity from their property as a down payment on the manufactured home, and the fourth received approval for up to $100,000 for a construction loan.

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[9] Fluctuating income refers to income that is unpredictable or tends to start and stop.

The multilayered financial support in the Pilot is largely viable as is, according to stakeholders, though they reported a few concerns with it.

- **A low-income participant needs to patch together funding and financing, but someone poor enough to qualify for the CAP agency funding might be too poor to qualify for a loan.** To be eligible for CAP agency weatherization funds, a participant must have an income below 200% of the Federal Poverty Level. At that income level, few people would be willing or able to accommodate an extra monthly payment following replacement.
- **Some funding and financing is available in geographically-limited areas.** The weatherization funds available through UCAN are only available in Douglas County, and the USDA Section 502 loans are only available in rural areas.
- **The timing of the incentive and subsidy require the homeowner to cover the down payment at the time of home purchase.** Manufactured home retailers require the customer to pay 50% of the home's cost upfront. But a Pilot participant would not receive the Energy Trust incentive or CAP agency grant until after the home has been sited and inspected. This can be a challenge for the homeowner to cover the upfront cost and pay interest on their loan while they wait for the incentive and subsidy. As one interviewed stakeholder described: "So many different funding sources are needed to make the projects pencil out, and each funding source has its own timeline, budget issues, and process steps. It's a real Herculean feat to make the stars line up at once for one of these projects."
- **Project costs are hard to predict.** Pilot stakeholders reported a lesson learned was that the estimated project cost was a lot higher than they expected, and it is hard to predict on a case-by-case basis. The loan amount is determined before the existing home has been decommissioned, and the new home sited. However, unexpected project costs arise during the decommissioning and site-preparation phases (see Section 3.4.1 for more). A labor shortage and legislation that changed hazardous materials charges increased project costs from what stakeholders had originally estimated.

### 3.3.2 Financial Support Received by Park Operators for Replacements

The park operators also put together multiple layers of funding to replace older manufactured homes in their parks. Saint Vincent de Paul received a small grant and a Community Development Block Grant (CBDG) loan from the Portland Housing Bureau to finance the park acquisition and improvement project. They used a combination of a bridge loan from a CDFI and a permanent loan to purchase the new units and complete the park project. They used the Energy Trust incentives to pay down the balance of the loan and converted what was remaining into a permanent loan with the bank. NeighborWorks Umpqua self-financed their project through their line of credit at the Oregon Community Foundation's Oregon Impact Fund and through support from the Network for Oregon Affordable Housing (NOAH). NeighborWorks Umpqua needed $400,000 upfront to cover the costs to purchase the homes, have them delivered, and installed. They reported their overall project costs were about $600,000.

## 3.4 Home Replacements

This section reviews the stages of replacing a manufactured home through the Pilot and the home replacements that have occurred to date.

### 3.4.1 Home Replacement Process

Replacing the manufactured home occurs in four stages: 1) selecting the new manufactured home; 2) decommissioning of the old home; 3) preparing the site for the new home; 4) and installing the new home. There are variable costs at each stage, which can make the prediction of overall project costs difficult. Total project costs for single-wide home replacements in the Pilot ranged from $75,000 to $123,000.

#### New Home Selection

**Pilot participants have flexibility to choose an efficient home that works best for them.** Pilot staff encourage participants to talk to more than one retailer and developed a list of retailers that participants can visit to shop for qualified homes. With participants buying homes from a variety of manufacturers, Pilot staff wanted to ensure that they would not have to request numerous customizations to meet the Pilot and other funders' requirements. For example, there was a minor issue when Pilot stakeholders learned that some new homes did not initially meet an ASHRAE 62.2 air ventilation standard that was required to use the CAP agency weatherization funds. Stakeholders were able to have a modified fan control installed in the home later so that it met ASHRAE's continuous ventilation requirements instead of the participant needing to have the factory modify it.

Pilot stakeholders decided to keep the home requirements simple for Pilot participation. The home must meet the minimum requirements of the Northwest Energy Efficient Manufactured Homes (NEEM) certification. Other than the efficiency requirement, participants can select the home and features that work for them and their plot of land. That freedom to choose can add complexity to the decision, though. An interviewed park operator likened picking out a new manufactured home to picking out a car. As he described:

> *"There are umpteen different models, floor plans, and upgrade options. Do I want the bronzed nickel finish? All these choices you're having to make can be overwhelming and costly."*

One interviewed participant who lives on private land and had purchased her new manufactured home at the time of the interview enjoyed having the options and modified a floor plan to suit her needs. She reported that the J&M sales representative was very helpful and ensured she got what she wanted. The participant selected a three-bedroom floor plan and altered it to be a two-bedroom, two-bathroom home.

**Plot size constraints arose as a major challenge most participants encountered when picking out their new home, whether in parks or not.** In parks, it can be a challenge to find a new home that will fit the existing lot dimensions and meet set-back code requirements. Many older parks drew their lot lines to densely pack in older, smaller homes and have not updated their plot sizes. As the industry has grown and regulatory codes have been updated, the newer manufactured homes are built larger. Even new or redesigned parks must strike a balance between maximizing the number of units in the park to allow for more residents versus having larger lot sizes for larger homes (and fewer residents). Siting the new, larger homes has created challenges to conform with set-back requirements. One participant with an older double-wide trailer from 1990 has had difficulty finding a new double-wide trailer that will fit in their space and comply with code.

An interviewed park operator reported needing to purchase homes from two different manufacturers to find the right sizes to fit on their plots. They also mentioned that figuring out the lot dimensions and the setbacks was not easy to understand. They needed to "measure the size of our lots multiple times because it was pretty confusing to try to figure out what would fit on what spots." At one plot, they needed to relocate the utility connections, so they were compatible with where the connections were in the new home.

This park operator noted that Pilot partners will need to provide technical assistance to the homeowners to ensure they measure dimensions correctly, understand the implications of utility connection locations, and communicate everything accurately to the retailer. They added that these technical activities were "not a big deal for them, but for an individual homeowner, that's a lot to deal with."

The individual homeowners we interviewed who had made it to this step were managing to address these technical requirements. One homeowner had to buy a smaller home than she initially desired to meet the county setback requirements on her land. The retailer gave her the specifications of where the utilities were in the new unit, and if the connections at the site are within 10 feet, the retailer can connect them. Her husband will do the measuring and may have to move some piping. She said that between her husband and herself, "I think we can measure things out and get it pretty close."

Pilot stakeholders noted that "dealers are notoriously opaque on the cost" because it is not always clear if the unit cost includes delivery and installation. It will be important for Pilot staff and stakeholders to educate potential participants to clarify with sales staff if delivery and installation are additional costs that will need to be paid later. The homeowner who purchased her home was savvy and communicated with the retailer about delivery and what that included.

After selecting a new home, it can take the manufacturer 14 weeks to build the home. However, the manufacturers have limited space for home construction and may not be able to construct 20 homes at once for park operators that want to order a batch. This is particularly an issue for park operators with multiple replacements. Delivery of 20 homes at once could cause issues for a park operator, because it could potentially take weeks to install 20 homes. Smaller batches of two to three homes at a time is more feasible for a manufacturer to construct and for the park operators to install. In fact, this is how replacements were handled at the Oakleaf park; the homes came in batches. Staging of replacements would also minimize the number of temporarily displaced residents at the same time and could allow for rotational temporary housing.

### Arrange Temporary Housing

**Park operators assist their park participants with arranging temporary housing, while some on private land owned a travel trailer they could stay in.** Saint Vincent de Paul arranged temporary housing for each of the Oakleaf park residents. They expected to place everyone at a hotel, but some residents had unfavorable opinions about the hotel. Only one participant we spoke with went to the hotel, though he stated, "a lot of us were there." The others each went to a duplex, an apartment, a single-family home, and the nearby Arbor Mobile Home Park. Oakleaf residents' housing costs were equal to their original rental prices and Saint Vincent de Paul paid any additional costs. Saint Vincent de Paul also arranged portable storage units for residents to store items they did not take with them to the temporary housing.

Two participants on private land reported they had a travel trailer they could stay in on their property while the manufactured home was being replaced. Another was debating whether to stay with family or friends or instead fix up their RV and stay in that, while showering at family and friends' homes. The fourth was still figuring this out at the time of the interview but reported that the length of time would influence them. If it will just be a couple weeks, they will make due in their garage on their property, but if it is longer than that, then they will likely do a short-term rental.

### Decommissioning

**The costs associated with decommissioning the site can be difficult to predict.** The old unit must be demolished following environmental laws, which means it needs to be inspected to determine if there are hazardous materials present such as lead-based paint, sewage, drug paraphernalia, or asbestos. If hazardous materials are found, a hazardous materials charge must be paid in addition to the inspection fee. An interviewed participant reported the hazardous materials inspection cost $400 and would have to pay the extra charge if asbestos was found. He said his septic tank also required inspection as part of this process.

After any necessary abatement, the unit is demolished and removed from the site. Two park operators reported decommissioning costs of $10,000 per unit before any hazardous-materials charges. During the Pilot period, a labor shortage and legislation that increased hazardous materials charges increased project costs from what stakeholders had originally estimated. There are permits associated with this step, and those costs vary by county. Stakeholders reported that the expensive and somewhat unpredictable decommissioning costs have been a challenge to financing the projects.

### Site Preparation

The main activity at this stage is to prepare the site to level the ground and pour a concrete pad. Stormwater drainage is also assessed and, if deemed inadequate, additional costs are incurred to rectify it. One homeowner on private land was thankful for her Energy Trust incentive because it would ensure she could cover this phase of her project because she must do some ground leveling and install a foundation.

One park operator experienced unexpected costs at this stage when they found black mud. They had to bring in material to stabilize the ground prior to pouring the concrete. There are also options to decide among at this stage. NeighborWorks Umpqua chose some options that would increase the homes' durability, such as including rebar in the concrete pad.

The other park operator reported scheduling challenges related to the site preparation. There is a narrow window of time to place the house on the concrete pad while it is curing. They reportedly had communication challenges with their retailer which made it difficult to ensure the homes would be delivered at the time appropriate for the concrete pad. The interviewed representative said a lesson they learned is to place a higher priority on customer service by the retailer. Future retailers they work with will need to demonstrate excellent customer service and communication to ensure there are no hiccups with the timing of delivery.

### New Home Installation

Once the site is ready and the home is delivered, it is ready to be installed. Installation involves attaching it to the foundation, skirting it, adding accessibility measures, and connecting its utilities. This needs to be done prior to the resident moving into the home. Pilot stakeholders and partners were again met with some unexpected costs at this stage. The new homes reportedly do not come with gutters or downspouts, which the park operators arranged to have installed to ensure rainwater goes where it should. One of them described this as "one of the more expensive post-construction elements." They also both reported needing to provide accessibility to the unit and build stairs up to the front door. One park operator considered deck covers for units with decks. At the Oakleaf park, a disabled resident needed a long ramp installed to his door and other adjustments inside. The staff needed extra time to build the ramp and make adjustments, which meant this resident was moved in last, though he said the new home was worth the wait.

The new mobile home also needs to be skirted at this time. Skirting is the material that goes from the base of the home to the ground. The contractors delivering the units are responsible for connecting the water and electricity hookups. Someone also goes inside the home and ensure everything is working properly, such as the toilets, showers, sinks, lights, locks, and HVAC system.

### 3.4.2 Replacements to Date and Upcoming Replacements

As of June 2020, park operators have completed replacements through the Pilot. Saint Vincent de Paul replaced 21 homes, and Pilot partner, NeighborWorks Umpqua, replaced four manufactured homes at their Newton Creek Manor park using the Energy Trust incentive (Table 6). As of July 2020, a homeowner on private land also completed a replacement.

Table 6. Completed Replacements by Park Operators to Date

| Park | Organization | Location | Number of Incented Replacements |
|---|---|---|---|
| Oakleaf | Saint Vincent de Paul | Portland, OR | 21 |
| Newton Creek Manor | NeighborWorks Umpqua | Roseburg, OR | 4 |
| | | **Total** | **25** |

Figure 11. Replacement Manufactured Homes at the Oakleaf Park

Photo courtesy of Energy Trust of Oregon.

**The Pilot has a robust pipeline of projects.** As of July 2020, 11 homes were scheduled for a pre-inspection and another 10 homes recently had their pre-inspection completed. These 21 homes were a mix of residents and homeowners in parks and include one homeowner on private land. Another nine homeowners on private land have had the pre-inspection results reviewed; Energy Trust has confirmed they are eligible and reserved an incentive for them. If all of the projects in the pipeline are completed, the Energy Trust Pilot will have supported the replacement of 65 manufactured homes.

### 3.4.3 Pilot Influence

**The Energy Trust incentive influenced park operators to replace their old inefficient manufactured homes and eased the process for private land homeowners.** For Saint Vincent de Paul, knowing the Energy Trust incentives would be available was "really important" when planning their park revitalization project. The interviewed representative reported that the incentive made it possible for them "to replace 100% of the units on the site with brand new, energy-efficient housing." They also described the incentive as having been "really critical for us" and "very effective" in reducing the barriers to replacing inefficient manufactured homes. They compared their Oakleaf experience to their stalled efforts to replace homes in parks outside of Energy Trust territory, saying the lack of financial support in the form of incentives is a main barrier.

NeighborWorks Umpqua, which received a reduced incentive for their gas-heated homes, reports they likely would have gone through with the replacements without the Energy Trust incentive. They noted that the incentive they received was still “a meaningful amount” and “really helped” their motivation to replace the homes. They added that, without those funds, they would have had to borrow the money and pay interest on it, so it benefitted their organization not to have to come up with or borrow those funds.

**The participant households on private land who are moving forward with replacement reported less Pilot influence.** All four said that in the absence of the Pilot, they most likely would have moved to a new manufactured home in the next 12 months but reported that the incentive will help them to do so or encouraged them to go through with it. The one who has purchased a new home reported that the availability of the incentive “was a big plus of wanting to go ahead and go through with it. It will help a lot” and made her feel like “I should do it now” after having considered replacement for the last three years.

Two of the other homeowners viewed the Energy Trust incentive as helping them offset the total project cost and not just the cost of the new home. Both noted significant costs associated with site preparation and felt more comfortable in their decision to buy the home, knowing that they had some funds to help with removing the old home and preparing the site. One of these had been considering replacing their home for three years, but only now is financially able to do so with the incentive contributing to that ability. Three of the private land participants had not yet purchased their home and could not speak to the selection of appliances and envelope features. They all reported they would buy a qualifying home with ENERGY STAR-rated features.

Nearly all (20 of 24) of the low-income residents at the Oakleaf and Umpqua Ranch parks reported that, absent the program, they would most likely stay in their manufactured home in the next 12 months. Three were unsure what they would do, and one was looking at new manufactured home floor plans hoping to move, but still figuring out financing. The last interviewed participant sold her manufactured home and purchased a single-family home (see Section 3.3.1).

**We calculated an influence score, similar to a net-to-gross score, of .82, which indicates the majority of participants were unlikely to complete a replacement in the absence of the Pilot.** The score takes into account the program’s influence on the household’s decision. Our calculation methods are as follows: First, we calculated a score based on answers about what the respondent would likely do in the next 12 months absent the program. If they would continue living in their current home or move to another older manufactured home, they were given a score of 0. If they would move to a new manufactured home or a site-built house or apartment building, they were given a score of 1. Those who reported they “did not know” what they would do (3 of 29) were assigned the mean score from the first 26 participants. The mean score was calculated for all 29 participants and then subtracted from 1, equaling .82.

The 29 respondents who make up this cohort and provided answers for this calculation are not likely to be representative of the cohort participating after new funds for manufactured home replacement become available (see last part of Section 3.6). The new funds will help reduce the upfront cost barrier and should allow some owner-occupied households in parks to participate that have not been able to previously. One would expect the influence score to be closer to 1.0 with the new cohort of participants.

## 3.5 Participant Experience in New Homes

We spoke with five residents who lived in the Oakleaf park before and after Saint Vincent de Paul’s revitalization project to hear about their experience in the new homes and how it compared to their old homes.

Three of the five were largely satisfied, while the fourth was overjoyed. The last resident preferred his original home that he had recently repaired to the Pilot-replaced home and reported his health was worse off in the new home. This respondent reported he suffered from "confusion" and that even his doctors could not confirm the veracity of his illness. We caution the reader when interpreting his answers because they are inconsistent with most participants' experience in the new homes.

### 3.5.1 New Home Conditions

**Residents were mostly pleased with the new homes, but noted they were smaller than their old homes.** Interviewed Oakleaf residents liked that everything was new, and they were the first to use appliances and fixtures in the kitchen and bathroom. One resident particularly appreciated the insulated walls and double pane windows because it made it comfortable and quiet inside. They also noted the whole house exhaust fan should prevent mold growing as it had at his old home. Knowing mold will not be an issue in this home makes him "feel a lot better," he said. For another resident, his new floor was his favorite thing because he could get around more easily in his walker and wheelchair. He described the new home as being like a "palace." He compared the new home to his old one:

> *I didn't realize it would be this awesome. It's really wonderful. It's not even a comparison to what I was living in before. This place has taken a complete 180-degree turn to what it is now.*

The residents' most common criticism was that the new home was smaller than their old one, which meant they could not fit all of their belongings in the new home as easily.[10] To accommodate, the residents were selling or donating items, though one rented a storage unit. Residents reported that two people could live comfortably in the new homes but that they were not suitable for families of three or more people. Some of the residents downsized from a double-wide to a single-wide manufactured home and that is the reason for reduced square footage.

**Some repairs have been needed in the new homes, even after only a few months.** While three of the five interviewed residents said nothing in their new homes needed repairs or maintenance, two mentioned multiple improvements they needed. One of these mentioned issues related to their sinks. The caulking around the kitchen and bathroom sink was reportedly "crumbling" after one month and the kitchen sink's spray hose needed to be tightened, but it has since started leaking again. The other resident had to fix loose cabinet doors and said his home settled oddly, so it developed some cracks.

### 3.5.2 Non-Energy Impacts

The non-energy benefits reported by residents in the new homes were significant, even with a small sample size and with the residents having lived in the homes fewer than six months.

**Most residents experienced substantially improved thermal comfort in the new homes (4 of 5).** The Oakleaf residents reported being much more comfortable temperature-wise in their new homes, with three of four rating it "a lot" better and the fourth saying it was "a little" better than their old home.[11] They noticed the heaters did not run as long when they came on and that the new homes retain the heat better. They also remarked on the absence of drafts in their homes.

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[10] One resident estimated the new home was 30 square feet smaller and another estimated it was 170 square feet smaller.

[11] The fifth resident was the resident with confusion. He had rated the old home as warm, dry, and comfortable and did not offer information about the comfort level of his new home. One would presume it is similarly warm, dry, and comfortable.

As a result, the participants reported improvements in their day-to-day lives. They no longer needed to wear jackets and sweaters in the house to stay warm. Another reported they sleep better at night because they do not need so many blankets on the bed. As an example, one resident said:

> *Back at the old trailer, there were times I had to wear a really huge sweater just to keep warm in winter because there were times when things weren't being done correctly; the machinery was just shot. Where I'm at now, I don't have to worry about those things.*

**Most participants reported their physical health improved a good amount after moving into the new home (4 of 5).** Of the four with improved health, two said it was "a lot better" and two said it was "moderately better." We list the health improvements by household below:

- For one household, their granddaughter's asthma had reportedly improved. The itchy and watery eyes the respondent and his wife frequently experienced in the old home had lessened in the new home.
- Another reported that he no longer experienced the upset stomach previously experienced frequently, and the vomiting previously experienced sometimes in the old home.[12]
- Another resident no longer experienced itchy and watery eyes. His cough that was persistent in the old home has gotten a lot better, and he only coughs once in a while now. His upset stomach that bothered him frequently before was gone, too. He reported still experiencing some dizziness and weakness but attributed that to a chronic health condition.
- The last resident with health improvements reported that he still experiences chest pain and weakness occasionally, but that his health had improved "60%" in the new home.

**Though difficult to measure, residents' mental health also showed improvements after home replacement because they had less to worry about (3 of 4).** The interviewer asked about the home issues the respondent reported worrying about in their intake interviews and whether they now worry less often, the same, or more often about these things in the new home. Generally, the respondents reported worrying less (Figure 12). For those who said they worry a lot less about things in their home, one reported their stress level and blood pressure had decreased as a result. The other commented on how much less he worries about his home by saying, "This home, it's like night and day difference. I feel comfortable [now]."

The person who worries somewhat less gave that answer because they did not know if home issues might arise after living in the house longer, but had reported no needed maintenance or repairs in the new home so far. Finally, the respondent who worries about the same, previously only worried about their home being cramped and cluttered, which they still contend within the smaller home.

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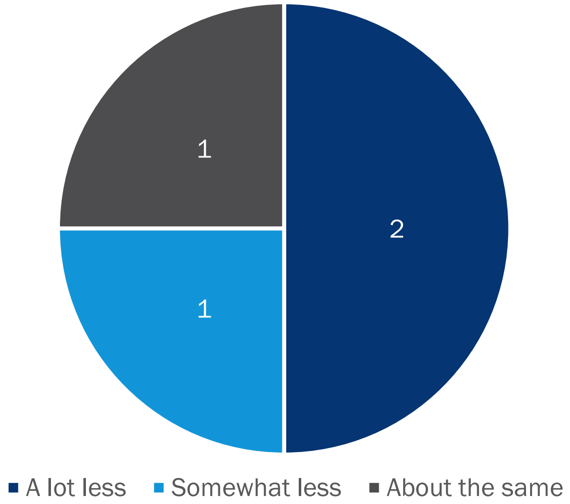
[12] This respondent attributed the health improvements to taking care of himself and seeing his doctor, and not the home.

Figure 12. Level of Worry in New Home Compared to Old Home (n=4)



**One resident elaborated on other non-energy benefits experienced, including pride and safety.** This resident invites people over with more frequency in the new home compared to the old home because he is no longer "ashamed or uncomfortable about people coming in." His answers suggested the new home was a point of pride and reported he was taking care to "keep this place looking nice" for the next resident. This same resident reported that he also feels "a lot safer" in the new home because the old home had broken windows, and now his windows are secure. He added that the park installed a tall fence around the perimeter with a code-based lock, which also improved sense of safety. The other interviewed residents all reported their sense of safety was about the same from the old home to the new home and invited guests over about the same amount.

### 3.5.3 Energy Bills

We interviewed the Oakleaf residents with electrically heated homes in the winter and they reflected upon their most recent bills. They did not perceive their recent electric bills to be a big savings over the electric bills they remembered from their previous manufactured homes. Due to the small sample of post-occupancy interviews and the short amount of time that residents were living in their homes before the interview, it is best to wait for information from the impact evaluation to judge the Pilot's energy impacts.

## 3.6 Stakeholder Coordination and Collaboration

Many stakeholder organizations came together to create the Manufactured Home Replacement Pilot. They recognized the intersecting health, financial, and security needs in these communities and understood how home replacements could contribute to improved quality of life. Yet, without a program model to follow, they had to work together and develop a playbook to make it happen.[13]

**Without Energy Trust's leadership, this Pilot would not have been possible,** agreed the interviewed stakeholders. Energy Trust brought together the coalition of stakeholders to fulfill the many roles needed. They recruited NOAH to help park operators finance replacements and worked with CASA to engage residents at cooperatively owned parks. They also engaged Craft3 to create a loan product appropriate for communities

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[13] Pilot staff are not making a real, actual, tangible playbook. We are using the term as a metaphor/analogy.

where the household owns the structure but not the land. Stakeholders from these organizations were highly satisfied with the support that Energy Trust has provided so far, and with their interactions and communications with Energy Trust staff. As one interviewed stakeholder put it from their perspective:

> *[The team] from Energy Trust have been so phenomenal to work with. When we have gotten distracted, they get us back on track. They're smart, they're easy to talk to, and they're clear in what they ask for. We wouldn't be where we are without them. The organizational spearheading has been integral in pushing this forward.*

Energy Trust supported the partner organizations by sharing research and data; bringing attention to the need for manufactured home replacement; and being a collaborative partner. One stakeholder said that Energy Trust's leadership and financial support "…is heartwarming and affirms that this is the right thing to do. The research that Energy Trust has done, the resources provided to reduce the cost, someone to throw ideas off of that knows what you're talking about are all really valuable things for us."

**Though the Pilot's progress may appear slow given the number of completed replacements, the stakeholders have made substantial headway in writing their playbook.** Pilot staff have had had to learn the hard way about the nuances and regulatory guidelines in several domains, each of which can quickly become complicated. As examples:

- Energy efficiency programs' cost-effectiveness criteria: how do we account for non-energy benefits?
- Local zoning and setback requirements: how does being in a flood plain affect the site, and how does that vary by county?
- Each funding source's eligibility criteria: how do we ensure the new homes meet the more stringent ASHRAE ventilation standard required to use weatherization funds?
- Responsible lending practices: how do we maximize the loan amount while minimizing any financial hardship for a low-income household?

Some successes from the Pilot are apparent; one of them is the attention this Pilot has drawn from other regions. Puget Sound Energy in Washington state reached out to Pilot staff to learn from them with a goal of replicating the Pilot for their manufactured housing communities. Craft3 reported that "people are coming to us from all over to learn from us or do this in their area." Other Pilot accomplishments include the robust and diverse network of partners that have come together to support the Pilot goals and the increasing interest among homeowners interested in using the Pilot.

Another indicator of the Pilot's success so far was the passing of House Bill 2896, which allocated $2.5 million to, among other things, provide loans to individuals to replace their old, inefficient manufactured homes and to support "safely decommissioning and disposing of a manufactured dwelling."[14] The Oregon legislature passed the bill in summer 2019 with unanimous support from both Republicans and Democrats. The promising results from the Pilot thus far, plus the potential to learn more about the non-energy benefits from households who complete replacement, were reasons policymakers gave for extending support. That state legislature support adds to the growing chorus that manufactured home replacement is a worthy endeavor for households, communities, and the grid. A Pilot staff member summarized the perspective on this Pilot:

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[14] House Bill 2869: https://olis.leg.state.or.us/liz/2019R1/Downloads/MeasureDocument/HB2896/Enrolled

> *When you look at the landscape of opportunity for a programmatic entity to support these types of homeowners to achieve better, safer, more affordable, and more efficient housing, there's few options beyond this one.*

Indeed, this Pilot has gotten the farthest in writing the playbook for manufactured home replacement.

## 3.7 The Future for Manufactured Home Replacement in Oregon

### 3.7.1 Expansion Plans

In their recurring meetings in 2018, stakeholders discussed whether to expand Pilot opportunity beyond the three initial parks and how best to do so given the Pilot goals. Factors they considered include the utility territories the park is sited in (if it is dual-fuel or not), its ownership structure, threat of park closure, local zoning laws, and the organizations that could serve as potential partners for those parks. They decided it would be worthwhile to expand their outreach.

Pilot stakeholders discussed the home replacement opportunity with the following groups to gauge their interest in the Pilot:

- Hood River Energy Plan's Energy Burden Committee for Hood River County
- Saint Vincent de Paul's Arbor Mobile Home Park in Portland
- South Central Oregon Economic Development District for Klamath Falls
- West-Side Pines Cooperative park in Bend
- Confederated Tribes of the Umatilla Indian Reservation Lucky 7 Trailer Court
- Park owners of gas-heated homes in Washington County

NeighborWorks Umpqua had also been looking for additional park preservation projects in which they could use the Pilot incentive. But they have been competing with well-heeled investors who can close on a park quickly. They gave an example of when they called an agent of a park up for sale. The agent had already received five offers over asking price and were going with an offer that could close in two weeks. As a nonprofit, NeighborWorks Umpqua cannot pay over the valued amount and their administrative processes take more than two weeks. Parks that investors are not making offers on are small, remote, and have lots of infrastructure issues; not a viable opportunity for NeighborWorks.

Saint Vincent de Paul has also looked into replacements in their other parks. However, they are outside Energy Trust territory and the absence of the Energy Trust incentive has made it difficult for them to move forward replacing old, inefficient homes at their parks in Lane County. Energy Trust has been working with OHCS and the Bonneville Power Administration (BPA) to allocate funds for home replacements outside of Energy Trust territory. BPA provides funds for home replacements through local utilities, but at $2,000, are much smaller than those available through Energy Trust.

CASA has six parks in Oregon other than Umpqua Ranch and is looking to make the Pilot offer available to those additional sites.

### 3.7.2 Future Program Needs or Possible Changes

**Pilot stakeholders reported their coalition might benefit from one additional type of partner**; a single point of contact that can shepherd the participant from beginning to end. None of the existing Pilot stakeholders are in a position where this role would fall naturally to them. This role of keeping track of where a participant is in the replacement process has been being performed jointly between Energy Trust, CLEAResult, CASA, and Craft3. Stakeholders were quick to add that if a new formal role were to be created, they did not want the participant to absorb the cost of providing it through increased home costs or decreased incentive costs. Pilot stakeholders will look into whether funds through a source like OHCS or Meyer Memorial Foundation can support such a service.

**The state of Oregon and its state-level agencies may have a larger role to play in manufactured home replacement.** Pilot stakeholders are eager to expand the manufactured home replacement support throughout Oregon, but most of the key financial support are not available everywhere in the state.

The weatherization funds are funneled from OHCS to the CAP agencies that provide the funds to eligible households in their service territories. When the decision to contribute the weatherization dollars is left to each CAP agency, Pilot staff must invest effort to recruit each one. A solution would be to bypass the CAP agencies and allow OHCS to allocate weatherization funds to home replacement at the state level. The Multifamily Energy Program shows a precedent for the state performing this role. Alternatively, the state could actively encourage all of Oregon's CAP agencies to promote the idea of replacement, so they become another outreach channel for the Pilot.

The $2,000 BPA incentive for manufactured home replacement available outside of Energy Trust service territory has appeared inadequate in stimulating interest. The USDA rural development loan offers attractive rates but is available only in rural areas and Pilot participants have yet to qualify for it. The additional funds coming from the state in HB2896 will be very useful in filling the gap that these funds leave behind.

**More completed projects will allow the stakeholders to better estimate project costs.** There is a $50,000 range between the least cost and highest cost replacements through the Pilot thus far (Table 7). As more homeowners participate in the Pilot and complete replacements, Pilot staff will be able to refine their project cost estimates, which will allow them to assign Pilot funds more accurately and have more focused preparatory conversations about project costs with potential participants.

Table 7. Range of Project Costs

| Project Aspect | Lower End | Higher End |
|---|---:|---:|
| New manufactured home | $52,000 | $83,000 |
| Site decommissioning (testing, demolition, removal) | $15,000 | $21,000 |
| Site preparation (concrete, gravel, leveling) | $3,000 | $9,000 |
| Installation (stairs, gutters, skirting) | $5,000 | $10,000 |
| **Total** | **$75,000** | **$123,000** |

# 4. Conclusions and Recommendations

We offer the following conclusions and recommendations:

**Conclusion 1:** There is a considerable need to replace pre-1994 manufactured homes in Oregon. Many of these homes are in disrepair. Roof leaks, cracks in the walls, holes in the floor, mold, and pests make the homes uncomfortable, worrisome, and potentially unhealthy to live in.

**Conclusion 2:** The Pilot is sufficiently resourced, attractive, and flexible enough to encourage manufactured home replacements inside and outside of the park context. Pilot staff have engaged stakeholders to facilitate replacements for residents in parks indiscriminate of whether the participants own the home, land, or neither. Pilot partners support homeowners who do and do not own their land and also engage park operators for replacements where tenants occupy the homes.

**Conclusion 3:** Each replacement project is unique due to the household's financial situation and the land plot the home is sited on. Each homeowner considers their assets and whether a loan is in their best interest. At the same time, loan decisions are complicated when project costs are hard to estimate. The cost to replace a single wide manufactured home can vary considerably and some of the costs are hard to predict. Individualized attention is necessary when home replacement projects occur on a case by case basis.

> **Recommendation:** Pilot staff should ensure continued or reinvigorated discussions with interested partner organizations and initiate discussions with other potential organizations to secure funding for a participant liaison role that can provide individualized support and be a point of contact to shepherd the participant.

**Conclusion 4:** The Pilot brings together a variety of financial support, including incentives, subsidies, grants, and low-interest loans, but most participants cannot qualify for all of them and some have had difficulty qualifying for any. Most of the Pilot's financial support is available in geographically restricted areas and only one of the state's 15 CAP agencies contributes weatherization funds to the Pilot. Soon, Oregon House Bill 2896 will provide additional funds for manufactured home replacement, which can potentially be used to supplement Pilot support.

> **Recommendation:** Pilot staff should investigate ways to make best use of the HB2896 funds and determine opportunities for combining them with Pilot funds to further reduce the cost of home replacements for participants. Pilot staff should also pursue the possibility of OHCS approving all of Oregon's CAP agencies to assign a portion of weatherization funds to manufactured home replacement.

**Conclusion 5:** Early post-occupancy findings point to substantial non-energy benefits for people who move from a pre-1994 manufactured home to a new, energy-efficient one. Thermal comfort was markedly improved, health conditions improved, and residents reported reduced stress and worry in the new homes. Some experienced pride in the new home and increased feelings of safety as well.

> **Recommendation:** Subsequent evaluations should include efforts to measure self-reported non-energy benefits.

# Appendix A. Energy Trust of Oregon Incentives

Table 8. Pilot Incentive Amounts by Home Type

| Home Type | Year Built | Climate Zone | Incentive for Electrically Heated Homes [a] | Incentive for Gas Heated Homes [a] |
|---|---|---|---|---|
| Single-wide | Pre-1976 | West of Cascades | $10,000 | $4,000 |
| | | East of Cascades | $15,000 | $7,500 |
| | 1976-1994 | West of Cascades | $7,500 | $3,000 |
| | | East of Cascades | $9,000 | $9,000 |
| Double-wide | Pre-1976 | West of Cascades | $15,000 | $7,500 |
| | | East of Cascades | $17,500 | $13,000 |
| | 1976-1994 | West of Cascades | $12,500 | $6,000 |
| | | East of Cascades | $15,000 | $15,000 |

[a] Incentive levels reflect conversion to like-sized home. Adjusted incentives are available for single to double-wide conversions.

# Appendix B. Participant and Resident Demographic Data

This appendix presents demographic data about the interviewed Oakleaf and Umpqua Ranch residents along with the five participants on private land.

About half the sample had lived in their home five years or less, while about half lived in their home six years or more (Table 8).

Table 9. Number of Years Lived in Current Home (n=29)

| Years Lived in Current Home | Number of Respondents |
|---|---|
| Under 2 years | 7 |
| 2-5 years | 8 |
| 6-10 years | 5 |
| 11-20 years | 6 |
| More than 20 years | 3 |

Participants commonly lived in one- or two-person households (Table 9). Eight households had children under 18 living there (8 of 29; 28%). A minority of households had a senior over 65 living there (5 of 28; 18%). Four households had veterans.

Table 10. Number of People in Household (n=29)

| Number of People in Household | Number of Respondents |
|---|---|
| 1 | 8 |
| 2 | 11 |
| 3 | 4 |
| 4 | 4 |
| 5+ | 2 |

Most Oakleaf and Umpqua Ranch participants could get around freely in their home (21 of 25; 84%). One mentioned that their overweight wife “has trouble getting around.” The others did not elaborate on mobility issues.

The residents in the Oakleaf and Umpqua Ranch parks had lower annual incomes than those on private land. While everyone in the parks reported pre-tax annual household income of under $50,000, three participants on private land reported incomes over $50,000 with one exceeding $100,000. Nearly half of the park participants (11 of 25; 44%) reported receiving Supplemental Security Income (SSI) or Social Security Disability (SSD) income.

Table 10 includes the income answers of 26 participants. An additional two park participants specified they earned less than $50,000 in the prior year but declined to provide a more detailed income answer. They are not reflected in Table 10. One other participant declined to answer.

Table 11. Household Income (n=26)

| Household Income | Number of Respondents |
|---|---|
| Less than $15,000 | 10 |
| $15,000 to $24,999 | 5 |

| Household Income | Number of Respondents |
|---|---|
| $25,000 to $34,999 | 5 |
| $35,000 to $49,999 | 3 |
| $50,000 to $59,999 | 1 |
| $60,000 to $74,999 | 0 |
| $75,000 to $100,000 | 1 |
| More than $100,000 | 1 |

Most interviewed participants identified as White (Table 11), two were Native American and one was African American. Five people voluntarily mentioned that another person in their household was nonwhite. These included one Filipino wife, one Hispanic wife, one Hispanic grandchild, a mixed-race son (half-Black), and another Native American (relationship unstated).

Table 12. Participant Race (n=28)

| Race | Number of Respondents |
|---|---|
| White or Caucasian | 25 |
| Native American | 2 |
| African American | 1 |

# Appendix C. Instruments

## Participant Intake Interview Guide

### Introduction

The Manufactured Home Placement/Replacement Program is available through [ORGANIZATION] and the Energy Trust of Oregon, with the mission to replace the homes of residents living and working in Oregon. The purpose of this survey is to understand which parts of this program are most important to residents of your community. We also want residents to know and understand the benefits and priorities of the program, which are the health and safety of you and your fellow residents, and to hear your thoughts about those benefits and priorities.

I have about 15 minutes worth of questions about your perspective on the program. Is this a good time to talk? Everything you say to me is confidential. We will combine your responses with those of other respondents, and we will not report anything in a way that would identify any individual respondent.

### Motivation for Participation [ASK ALL]

Q1. [*Skip if this is the first the respondent is hearing about the program*:] What was your reaction when you first heard about this program to help people replace their manufactured homes? [*If needed*:] Were you excited? Were you skeptical?

1. Why was that?

Q2. I'm going to read a list of ways someone might benefit from replacing an older manufactured home with a new one. For each one, please tell me how likely you think it is that someone replacing their home would experience that benefit in a meaningful way. Please answer on a scale from one to five where one is not at all likely, and five is very likely.

1. You can keep the temperature more comfortable inside your home
2. Lower energy bills
3. Less need for maintenance and repair
4. Increased safety
5. Improvement in health issues like allergies and asthma
6. Having a brand new home where everything is up-to-date

### Concerns/Barriers to Participation [ASK ALL]

Q3. What do you think will be the most difficult part of replacing your current home with a new manufactured home?

Q4. What concerns do you have, if any, about <u>the process of replacing your home</u>?

1. [*If not addressed*:] Are the upfront costs of replacing your home manageable?

Q5. What concerns do you have, if any, about <u>living in the new home after replacement</u>?

1. [*If not addressed*:] Is the increase in your monthly housing costs – like loan payments or rent – reasonable?

Q6. [*If respondent has decided not to move forward with home replacement or has not yet decided to move forward*] What are the most important things that caused you/might cause you to decide not to replace your home?

[*Allow the respondent to give an open-ended answer. For any items not addressed, ask*:] What about:

1. The upfront cost of replacing your home
2. The increased monthly housing costs
3. The need to move out during the replacement process
4. Uncertainty about how long you will continue living in your home
5. The potential that the replacement home would not be the same size or layout as your current home
6. The potential that the replacement home would change the amount of usable space available on your lot

## Program Influence [ASK ALL]

Q7. If this program to help people replace older manufactured homes was not available, which of these things best describes what you would do in the next 12 months? Would you…

1. Continue living in your current home
2. Move to another older manufactured home
3. Move to a new manufactured home
4. Move to a site-built house or apartment building

96. Other, please specify:
98. Don't know

Q8. [*If respondent would continue living in their current home or move to another older manufactured home (skip for SVDP Parks):*] The program offers different types of support in helping people replace their older manufactured homes. We'd like to know how important each one is in your decision to replace your home. On a scale of one to five, with one meaning not at all important and five meaning very important, how important is…

1. The grants that are available to reduce the overall cost of replacing your home
2. The availability of a loan to help repay the costs not covered by grants
3. Help with the process of replacing your home

Q9. [*Skip for SVDP parks*:] What else, if anything, does the program offer that was important in your decision to replace your home?

## Pre-Replacement Housing Conditions [ASK ALL]

Thanks for your responses so far. Now I have a few questions about your current home. This program to help people replace their manufactured homes is new, and these questions will help us understand all the ways people benefit from moving into a new home.

Q10. How long have you lived in your current home?

1. [*If less than 5 years*:] Before you moved into your current home, did you live in another manufactured home, or in some other type of housing?

Q11. What do you like most about your current home?

Q12. How would you describe the condition of your current home?

Q13. [*If not addressed*:] Do you feel that your home needs repairs?

1. What needs to be done?
2. What, if anything, is preventing you from getting your home repairs done?

Q14. How comfortable would you rate your current home?

1. What are the main issues that make your home uncomfortable?

Q15. How do you heat your home?

Q16. Do you use plug-in space heaters?

1. How many do you have?
2. What type of plug-in heaters do you use?
3. How often do you use plug-in heaters during the winter?

Q17. Do you use a wood stove or fireplace to heat your home?

1. How often do you heat your home with wood?

Q18. Is your home drafty in the winter?

Q19. Is your home leaky when it rains?

Q20. Is there anything about your home that makes you feel unsafe? [PROBE: uneven floors, fear of tripping, mold, etc.]

Q21. Since moving into your current home, have you or anyone else in your household experienced any health conditions that the condition of your home has either caused or made worse?

1. [If yes:] What were they?
2. [If yes:] What about your home caused the condition or made it worse?

Q22. In some cases, living in a new home can help improve people's health. We want to understand if this is one of the ways people benefit from this program to help people replace their manufactured homes. I'm going to read a list of health issues that can be affected by housing conditions. For each one, please tell me whether you or someone else in your household have experienced it frequently, a few times, or not at all in the past 30 days [*Acknowledge any conditions mentioned in Q21*]:

| Condition | Experienced Frequently | | Experienced a Few Times | | Did Not Experience | |
|---|---|---|---|---|---|---|
| | Respondent | Someone else in Household | Respondent | Someone else in household | Respondent | Someone else in household |
| 1. Asthma | | | | | | |
| 2. Watery eyes | | | | | | |
| 3. Itchy eyes | | | | | | |
| 4. Persistent cough | | | | | | |
| 5. Tightness in chest | | | | | | |
| 6. Chest pain | | | | | | |
| 7. Upset stomach | | | | | | |
| 8. Vomiting | | | | | | |
| 9. Dizziness | | | | | | |
| 10. Weakness | | | | | | |
| 11. Confusion | | | | | | |
| 12. Anything else? | | | | | | |

Q23. Do you, or does anyone else in your household, smoke tobacco?

Q24. What, if anything, are the most important issues that have been creating worry or stress for you in the past 30 days?

Q25. [*Ask about any not addressed in Q23*:] In the last 30 days, have any of these issues created worry or stress for you?

1. The condition of your home
2. Paying your bills
3. The possibility of having your utilities shut off
4. Your health
5. The health of someone who lives with you
6. Having enough to eat

Q26. Is there anything else you would like to tell me about the condition of your home?

## Demographics/Firmographics [ASK ALL]

Q27. How many people live in your home?

1. Including yourself, can everyone in your home get around freely, without the help of others?
2. Including yourself, how many people who live in your home are age 65 and older?
3. How many people who live in your home are 18 and younger?
4. Including yourself, how many people who live in your home are veterans?

Q28. Are you, or is anyone else in your household, a veteran?

1. I am a veteran
2. Someone else in my household is a veteran
3. No one in my household is a veteran

98. Don't know

99. Refused

Q29. Do you, or does anyone else in your household, receive Supplemental Security Income (SSI) or Social Security Disability (SSD) income?

1. Yes
2. No
98. Don't know
99. Refused

Q30. Which of the following ranges describes your 2016 total household income before taxes? Was it…

1. Less than $50,000
2. $50,000 to under $100,000
3. $100,000 or more
98. [*Do not read*] Don't know
99. [*Do not read*] Refused

Q31. [*If Q28=1*] Is it:

1. Less than $15,000
2. $15,000 to under $20,000
3. $20,000 to under $25,000
4. $25,000 to under $30,000
5. $30,000 to under $35,000
6. $35,000 to under $40,000
7. $40,000 to under $45,000
8. $45,000 to under $50,000
98. [*Do not read*] Don't know
99. [*Do not read*] Refused

Q32. [*If Q28=2*] Is it:

1. $50,000 to under $60,000
2. $60,000 to under $75,000
3. $75,000 to under $100,000
98. [*Do not read*] Don't know
99. [*Do not read*] Refused

Q33. [*If Q24=3*] Is it:

1. $100,000 to under $150,000
2. $150,000 to under $200,000
3. Over $200,000
98. [*Do not read*] Don't know
99. [*Do not read*] Refused

Q34. With which of the following racial or ethnic groups do you identify? Do you consider yourself… [*Respondent can choose multiple options*]

1. White or Caucasian
2. Black or African American

3. Latino, Hispanic, or Mexican
4. Asian or Pacific Islander
5. Native American
6. Middle Eastern or North African
96. [*Do not read*] Other, please specify:
99. [*Do not read*] Refused

## Participant Post-Move In Interview Guide

### Introduction

Hi. My name is _______, and I'm calling on behalf of Energy Trust of Oregon regarding the home replacement program.

[If needed] The Manufactured Home Placement/Replacement Program is available through [PARK ORGANIZATION] and the Energy Trust of Oregon, with the mission to replace the homes of residents living and working in Oregon.

Now that you have gone through the process of replacing your home, we wanted to speak with you so we can understand which parts of the program are working well for participants and which parts could work better. We also want to hear your thoughts about benefits. As one of the first participants in this new program, your feedback is very valuable to us.

I have about 25 minutes worth of questions. Is this a good time to talk? Everything you say to me is confidential. We will combine yours with those of other respondents, and we will not report anything in a way that would identify any individual respondent.

### Replacement Process [ASK ALL]

Thank you for talking with us in [year] about why you were interested in the program. My first questions today are about the replacement process.

Q1. How long did it take between when you moved out of your old home and when you moved into your new one?

1. Where did you go?
2. Where did you put your things?
3. How difficult was it for you to find a place to stay during that time?
4. How disruptive was that temporary displacement in your day-to-day life? [Probe for challenges related to pets or children's school districts]

Q2. [SKIP TO Q4 FOR OAKLEAF] Now I have some questions about getting a loan for the new home. What, if anything was difficult about applying for the loan to replace your home?

1. What concerns, if any, did you have about applying for the loan?
2. What help, if any, did you receive in applying for the loan(s)? [If any] How useful was that help in applying for the loan?
3. How long did it take to receive the loan(s) you applied for? Did this cause any delays in your home replacement project?

Q3. [If not mentioned in Q2_2] Did you get credit counseling or homeowner counseling through the program?

1. [IF YES] How helpful was that support? Why?

Q4. Have your monthly housing-related payments gone up or gone down since moving into your new home?

1. [IF YES] Was this change expected?
2. [IF YES AND WENT UP] How challenging has it been to make these increased payments?

Q5. Thinking broadly now, what about the process of replacing your home went well?

Q6. What was the most difficult part of replacing your home?

## Replacement Benefits [ASK ALL]

Now I have some questions for you about your experience living in your new manufactured home.

Q7. So far, has your new home met your expectations?

1. Why/Why not?

Q8. [*INTERVIEWER: Check prior interview for concerns/worries they had*] Now thinking about things like [INSERT: for example, sagging roofs or roof leaks or pests] do you feel like you worry less often, worry about the same, or worry more often in your new home?

1. How has that [lower/higher] level of worry affected your day-to-day life? [IF NEEDED: MORE: Perhaps you're apprehensive over the new items and don't want them to get broken. FEWER: Perhaps you have the freedom to use your whole home or are less anxious about how things are affecting your health.]
2. Now I'd like to know how much [more/less] you worry. Would you say you worry a lot [more/less], somewhat [more/less] or just a little [more/less]?

Q9. How does your new home feel temperature-wise compared to your old home? [If needed, is it more or less comfortable?]

1. [IF YES] What have you noticed? [Probe on fewer drafts?]
2. How has that affected your day-to-day life? I'm thinking of things maybe like not having to wear a jacket indoors during winter; not needing to get wood for a wood-fired stove.
3. Now I'd like to know how much [more/less] comfortable you are in your new home. Would you say you're a lot [more/less] comfortable, somewhat [more/less] comfortable, or just a little bit [more/less comfortable]?

Q10. [*Interviewer – prior to interview, input answers into this chart from prior interview and ask specifically about issues they mentioned before.*]

| Condition | Respondent or someone in household | Frequency |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

Last time you mentioned to our team that you or someone in hour household experienced [INSERT ITEM & FREQUENCY FOR EACH CONDITION LISTED ABOVE]. For each, I'd like to know if you still experience that the same amount, if you still experience it but less often, or if you don't experience it at all anymore. Let's start with…

| Condition | Still Experience Frequently | | Still Experience Some | | Do Not Experience Anymore | |
|---|---|---|---|---|---|---|
| | Respondent | Someone else in Household | Respondent | Someone else in household | Respondent | Someone else in household |
| 1. Asthma | | | | | | |
| 2. Watery eyes | | | | | | |
| 3. Itchy eyes | | | | | | |
| 4. Persistent cough | | | | | | |
| 5. Tightness in chest | | | | | | |
| 6. Chest pain | | | | | | |
| 7. Upset stomach | | | | | | |
| 8. Vomiting | | | | | | |
| 9. Dizziness | | | | | | |
| 10. Weakness | | | | | | |
| 11. Confusion | | | | | | |
| 12. Anything else? | | | | | | |

1. [ASK IF NOT IMPROVED] Okay, it sounds like not much has gotten better in the new home. Is that right?
2. [ASK IF IMPROVED] How have these health improvements affected your day-to-day life, if at all? [IF NEEDED: Perhaps you don't restrict activity as much you used to, or you don't need to buy medicine as often?]
3. [ASK IF IMPROVED] Please tell me whether your health or the health of someone living with you has improved a little, somewhat, or a lot.

Q11. Would you say you or any of your family members have changed in how often you invite guests to your home? Why is that?

1. [IF UNCLEAR] Would you say that's been a positive change in your life?
2. [If YES TO Q11_1] To what extent has that improved your life- a little, somewhat, or a lot?

Q12. How do your energy bills compare to the energy bills you received at your old home?

1. Why do you think that is?
2. [IF LOWER] What have you been able to use the extra money on? [Probes: more food, enjoyable activities, transportation, other bills or debts, etc.]
3. [IF LOWER] To what extent would you say this has improved your life – a little, somewhat, or a lot?
4. [IF HIGHER] To what extent have the increased bills negatively affected your life – a little, somewhat, or a lot?

Q13. How would you say your feelings of safety in your new home compare to your old home? [If needed: If your old home had doors or windows that didn't lock well, do you feel more secure in your new home, like it'd be harder for someone to break in?]

1. [IF SAFER] Would you say you feel a little safer, somewhat safer, or a lot safer?
2. [IF LESS SAFE] Would you say you feel a little less safe, somewhat less safe, or a lot less safe?

Q14. Since moving into your new home, have you had to do any maintenance or have anything repaired?

1. [IF YES] What needed repair or maintenance?
2. [IF UNCLEAR] Why did it need repair or maintenance?

Q15. We're almost done with the interview. Just a few more questions. What are your favorite things about your new home?

Q16. Is there anything you don't like about your new home? [PROBE: uneven floors, leaks, mold, mice, cockroaches, etc.]

### Closing [ASK ALL]

Q17. Now that you have replaced your home, what advice would you give to someone who was just starting to consider whether they should do the same thing?

Q18. What advice would you give the people running this program to make it go more smoothly for the residents or to otherwise improve it? [*Interviewer: if they mention specific people, try to find out which organization the person works at; for example, a WAP program, a bank/loan organization, CLEAResult, Energy Trust. Respondent may not know*.]

Q19. Those are all the questions I had prepared. Is there anything else you think is important for me to know about the process of replacing your manufactured home or about any benefits or concerns with your replacement?

## Pilot Staff or Partner Interview Guide 2017

### Introduction

Thank you for talking with us today. As we mentioned in our email, Research Into Action was hired by the Energy Trust of Oregon to evaluate the manufactured home replacement program. As a part of that evaluation we are talking with organizations that Energy Trust has partnered with to deliver the program. We will be talking with these partners about every six months. The goal of this initial interview is to get a better understanding of the pilot, your goals and objectives for participation, and anticipated challenges and opportunities.

The interview should take about 30 minutes, is now still a good time?

Great, and do you mind if I record the call? [IF NEEDED] this is just for my note-taking purposes. We will not identify you in our reporting of our findings.

## Instrument

Q1. How long has Energy Trust been working on the manufactured home replacement program?

1. How did your involvement come about?

Q2. When you first heard about the manufactured home replacement program, what was your reaction?

1. What was attractive about the idea?
2. What, if anything, were you skeptical about?

Q3. Please walk me through how the manufactured home replacement program will work in the communities your organization supports.

1. How will you identify potential homes for replacement, and how will you approach the owners/residents about the opportunity?
2. What challenges, if any, have you/do you expect to encounter with recruitment?
3. What, if anything, have you done/do you expect to do to overcome these challenges?
4. What type of support will you offer to residents/participants through the home replacement process?

Q4. What are your organization's goals for the manufactured home replacement program? [*Probe on goals during the pilot and goals after the pilot*]

1. How well do you anticipate the program's offerings will fit with the other types of support you provide?

Q5. From your perspective, what type of support does Energy Trust need to bring to the program for it to be successful? [*If needed, probe on funding, expertise, partnerships with other organizations, etc.*]

1. So far, has Energy Trust provided the support needed for the program to be successful?

Q6. Are you partnering with, or receiving support from, organizations other than Energy Trust? If so, what type of support do these organizations need to bring to the program for it to be successful? [*If needed, probe on funding, expertise, partnerships with other organizations, etc.*]

1. So far, have your additional partners provided the support needed for the program to be successful?

Q7. How has your experience working with Energy Trust been?

1. How frequently are you in contact with Energy Trust?
2. What challenges, if any, have you faced in your interactions or communications with Energy Trust?
3. How, if at all, have those challenges been resolved?
4. [*If working with other partners*:] How has coordination between Energy Trust and your other partners gone?

Q8. What do you anticipate will be the most important ways people will benefit from replacing their older manufactured homes?

Q9. Who do you see as an ideal candidate to replace their manufactured home through this program? Why do you say that?

1. Do you anticipate that the people who would benefit most from replacing their homes will participate in this program? Why or why not?
2. What types of manufactured home residents do you anticipate will be most likely to participate?

Q10. What do you see as the most important barriers that prevent people from replacing older manufactured homes with new, energy efficient ones?

1. Which of those barriers do you think the program will effectively address?
2. What barriers does the program not address? [*If needed: What might prevent someone from taking the pilot's offer to replace their home*?]
3. What would it take for the program to address those remaining barriers?

Q11. Are there any particular groups or types of people that you anticipate will face greater barriers to replacing their manufactured homes?

1. Are there any particular groups that will face fewer barriers?

In closing, we'd like to ask some broad questions about the manufactured home replacement program.

Q12. From your perspective, what would a successful program look like?

1. How would you measure that success?

Q13. What are the greatest challenges in terms of reaching this audience or implementing this program?

Q14. Those are all the questions I had prepared, is there anything else you think I should know as we work with Energy Trust to identify ways to refine the pilot?

## Pilot Staff or Partner Interview Guide 2020

### Introduction

Thank you for making the time to talk with us today. As mentioned in the email, I am working with the Energy Trust of Oregon to evaluate the manufactured home replacement pilot program. As a part of that evaluation we are talking with organizations that Energy Trust has partnered with to deliver the program. The goal of this interview is to get an understanding of how everything has gone so far, hear about any challenges you may have encountered with recruitment or financing, lessons you've learned, and the future for manufactured home replacement.

The interview should take about 45 minutes. Do you have any questions for me?

Great, and do you mind if I record the call? [IF NEEDED] this is just for my note-taking purposes. We will not identify you in our reporting of our findings.

## Recruitment [ASK STAKEHOLDERS 1, 2, 3, & 4]

Let's start with recruiting residents.

Q1. How do you identify good candidate households for participation?

Q2. How have residents, both participating and not, responded to the program?

1. [If unclear] What differences did you notice between those who participated and those who didn't?
2. Was the number of participants more or less or about the same as you expected?

Q3. What types of manufactured home residents decided to participate?

1. Are they different from the types you expected or that would benefit most from this program?

Q4. What challenges have you faced with recruitment?

1. How, if at all, have you been able to overcome these challenges?

Q5. What do you know now about the recruitment process that you wish you would have known at the beginning?

Q6. Did you have any challenges associated with finding new manufactured homes that suited the residents in terms of size or layout? If yes, what were they?

Q7. [Skip for stakeholder 4] How did your organization support participants with transitional housing, if at all? [If needed: did you help find them options for temporary housing? Find services for moving or storing their things?]

1. How did that whole process go? [Of the participants getting temporary housing]

Q8. [*Skip for stakeholders 2*] How has your organization informed and supported candidate households as they explore home replacement? [*For stakeholder 4 – phrasing could be: How does Neighborworks intend on informing and supporting Newton Creek residents interested in replacing their owned homes*?]

## Replacement Process [ASK STAKEHOLDERS 1, 2 & 3]

Q9. Please summarize for me what stage your organization is at in the process of replacing homes?

1. [*If park representative*] How many people at your site decided to participate?
2. [*If park representative*] And, about how many expressed interest in having their home replaced at some point?

Q10. Please describe for me the coordination and effort it took on your organization's part to facilitate the removal of the old homes and the arrival of the new ones?

1. Is that about what you were expecting?
2. How did that affect the pilot's timeline? [*If needed, how did it affect the pilot's momentum or progress*?]

Q11. What did you learn from the replacement process that you wish you would have known at the start?

## Financing [ASK STAKEHOLDERS 2 & 4]

Let's switch gears a little bit. My next questions relate to financing.

Q12. Tell me how it went for your organization as you secured financing to purchase the units.

1. [*If unclear*] How easy or hard was that?
2. [*If unclear*] Was it a lengthy process or did it go pretty quickly?
3. [*If unclear*] Where did you get financing from (what organizations)?

Q13. How many new homes were you able to buy?

Q14. If you were not involved in the Energy Trust home replacement pilot, how likely do you think your organization would have been to obtain financing to replace these older manufactured homes? Why do you say that?

## Financing [ASK STAKEHOLDERS 1, 3, 5, 6, & 7]

Let's switch gears a little bit. My next questions relate to financial support available through the pilot.

Q15. How has your organization been involved in securing funding and financing opportunities to offer potential participants (loans and grants)?

Q16. [*Ask stakeholder 5 only*] What did you consider when developing the financing package for pilot participants? [*If needed: Expected amount of down payment, appropriate loan term length; homeowner ability to pay off loan*]

Q17. What financial characteristics make a household a good candidate for participation?

Q18. How has your organization supported candidate households as they pursue grants or financing options?

Q19. What types of grants or financing have participants been able to obtain?

Q20. Why has it been difficult for potential participants to acquire financing?

1. Why was that the case/Why do you say that?
2. [*If unclear*] How much support did they need to follow the financing process?

Q21. Do you know about what proportion of potential participants dropped out because they had trouble with financing or for other financial reasons?

1. What percent dropped out for other reasons?

Q22. [*Ask stakeholder 6 only*] How do homeowners qualify for grants through your organization?

Q23. [*Ask stakeholder 6 only*] How many of the people who applied for your grants to use with this pilot qualified for them?

Q24. [*Ask stakeholder 6 only*] How has the process gone of your organization delivering funding commitment letters to homeowners who qualify for funding prior to financing?

Q25. I know the pilot brings together funding and financing from different agencies. What's the viability of the current financial support the pilot is providing; are they key changes that you think need to be made or is it viable as it is?

1. [*If not clear*] Is the financial support sustainable or will it go away?

Q26. What type of financial support would be required for the majority of homeowners who did not qualify to be able to replace their homes?

1. [*If yes*] What are they?
2. [*If no*] Why do you say that?

Q27. What do you know now about financing in a pilot program like this that you wish you would have known at the beginning?

## Working with Pilot Partners & the Future of the Pilot [ASK ALL]

We're close to the end of the interview. My last questions are about working with pilot partners and what you anticipate will make a manufactured home replacement program work well in the future.

Q28. How has your experience working with the other pilot partners been?

1. What challenges, if any, have you faced in your interactions or communications with your partners?
2. How, if at all, have those challenges been resolved?

Q29. Are there any new types of partners you think need to be brought in to support the pilot as it becomes a program?

1. [*If unclear*] What would those partners provide that isn't being done currently?

Q30. How will your organization continue to be involved in a manufactured home replacement program, if at all?

Q31. What sorts of benefits do you think this program will have for the residents who moved into new manufactured homes?

Q32. In your opinion, does the Energy Trust pilot effectively address barriers to replacing manufactured homes? Why do you say that?

1. What barriers does the program not address? [*If needed: What might prevent someone from taking the pilot's offer to replace their home*?]
2. What would it take for the program to address those remaining barriers?

Q33. What is the one biggest change that you think would help improve the program? [*If needed: help residents with financing more; help residents with finding a temporary home more; identify more models of homes to be offered, etc.*]

## Closing [ASK ALL]

Q34. Those are all the questions I had prepared, is there anything else you think is important for me to know as we work with Energy Trust to identify ways to refine the pilot?

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EXHIBIT MR-5

# A New State of the Art: Zero Energy Modular Multifamily Construction

**Final Report, Project DE-EE0009072**

**Prepared by VEIC**

December 2023

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# Acronyms

BAU: Business as usual

BEM: Building Energy Modeling

DES: Discrete Even Simulation

DfMA: Design for Manufacturing and Assembly

DOAS: Dedicated Outdoor Air System

DOE: Department of Energy

EE: Energy Efficiency

HERS: Home Energy Rating System

IECC: International Energy Conservation Code

MEP Systems: Mechanical, Electrical, and Plumbing Systems

NYSERDA: New York State Energy, Research and Development Authority

OS: Open Studio

PAT: Parametric Analysis Tool

RESNET: Residential Energy Services Network

VRF: Variable Refrigerant Flow

ZEM: Zero Energy Modular

ZERH: Zero Energy Ready Homes

# Executive Summary

In 2020, the U.S. Department of Energy's Building Technologies Office (BTO) launched the Advanced Building Construction (ABC) Initiative. This initiative aimed to integrate energy efficiency into high-production construction practices. One focus area of the initiative is off-site construction, an approach that may achieve scalable, efficient, and high-performing construction buildings through process standardization. This report presents the findings and recommendations from our ABC Initiative project: A New State of the Art: Zero-Energy Modular Multifamily Construction System. The objectives of the BTO-funded project are to:

1) Achieve energy performance 50% better than the 2018 International Energy Conservation Code (IECC).
2) Achieve this level of energy performance at no additional cost

VEIC worked with Louisiana State University (LSU), National Renewal Energy Lab (NREL), [the project team], and industry partners at the Mod Coach, KBS, and Solar Home Factory to identify and analyze multifamily business designs and modular construction practices. These designs and processes hold the promise of achieving the goals set out by the DOE.

The project team designed five case studies to determine if modular construction can achieve 50% better efficiency than the IECC at no extra cost. From there, the team could analyze and compare the results of baseline practices to these case studies of emerging industry practices that hold the potential to drive down costs while delivering high-quality, durable, and healthy multifamily buildings. The team drew on recent pilot programs and field experience and chose the following topics to investigate:

1) How to optimize multifamily unit design for factory construction.

2) How to leverage energy and cost modeling.

3) The feasibility of zero-energy factories.

4) How to integrate energy efficiency into an existing factory line.

5) How to integrate energy efficiency quality assurance and quality control (QA/QC) into existing processes.

The following sections summarize major findings and accomplishments of these topic areas.

### Optimizing multifamily unit design for factory construction

The team explored several ways to increase the amount of multifamily unit construction that can take place in the factory. For business-as-usual modular construction, approximately 80% of the building is constructed in the factory and 20% of construction is finished on site. Typical onsite construction includes exterior siding, insulation, air sealing, heating, ventilation, and air conditioning (HVAC).  For buildings that include solar PV and batteries, additional on-site work is required to install those systems. By increasing the percentage of construction that takes place in the factory, there is an opportunity to maintain continuity, reduce handoffs between trades, and increase labor efficiencies, which will ultimately drive down costs.

To support this goal, the team focused on "modularized" multifamily unit designs with the prime opportunities being apartment units and HVAC systems. The team identified an example multifamily building floor plan layout with three types of apartment units. Each unit type corresponds to a volumetric module (or space) which can reduce variability on the factory production line, in turn bringing more certainty to the production process. The team found that factories can effectively sequence the three types to develop an efficient construction schedule.

An apartment layout contained within a single volumetric module eliminates module-module mateline penetrations, or spaces where two separate modules meet. Since mateline penetrations require extra plumbing, electric, and off-site air sealing, containing these units within a single module allows for more of the construction to take place in the factory. Standardizing the mechanical systems both on a programmatic level (in one apartment) and on a spacial level (in one volumetric module) also eliminates the need for module-module mateline penetrations for ducting, running refrigerant lines, and distributing hot water.

The project team's work showed that it is feasible to “modularize” the design of a multifamily building and corresponding systems to maximize construction in the factory. The materials and equipment used for construction can be standardized off-the-shelf components that do not require custom project-by-project design, engineering, product customization, and non-standardized approval processes. All of these factors help increase efficiency and reduce costs.

### Leveraging energy and cost modeling

The project team used building energy modeling and cost modeling to analyze whether a multifamily building can meet the project goal of energy performance 50% better than 2018 IECC at no additional upfront cost. We ran 50,000 energy modeling scenarios in OpenStudio to develop three energy efficiency packages: one that focused on efficient mechanical systems, one that focused on improved envelope, and one that included elements of both efficiency mechanical systems and improved envelope. We performed cost modeling in Excel using a combination of published data and detailed cost data on materials, labor, and overhead provided by our modular factory partner.

Our three energy-efficiency prescriptive packages achieved 50% better energy performance. Our modeling showed that the zero-energy modular multifamily building costs more than the baseline scenario (11%-14%), but the energy efficiency packages were a small part of overall project cost (3%-6%). Our top-down cost modeling results show that under our current scenario, modular construction cannot yet achieve 50% better than site-built code at no extra cost solely through savings from material waste and labor quality. This case study highlights a key challenge associated with using construction costs as a metric: actual costs are difficult to obtain and normalize across projects.

**Feasibility of zero energy factories**

A modular construction system devoted to ultra-efficient, high-performance construction begins with the factory itself. We used energy modeling to explore if all-electric, high-performance factories with ventilation could be cost-effective to own and operate relative to more standard modular factories. Our goal is to create a factory design that is a comfortable and safe environment for workers while minimizing energy use. Our modeling compares a baseline, traditional modular factory to an efficient, all-electric factory.

We modeled over 1,000 scenarios in the OS Parametric Analysis Tool (PAT), capturing the combination variables listed in Table 13 below. 360 models remained for analysis after excluding the unintended or unrealistic scenarios. We used 2018 energy costs (at industrial building rates) available through NYSERDA for the modeling.[1, 2] Both the baseline and target factory are assumed to be 207,000 square feet and located in Albany, NY.

Our modeling showed that an all-electric modular factory can be much more cost-effective to operate than a traditional factory powered by propane, electricity, and gas-unit heaters. The HVAC target scenarios reduced annual energy costs by more than 60%. The HVAC system type has less impact on building energy use when the building is highly airtight. However, even with the highest building airtightness still have lower energy costs than gas-unit heaters and PSZ-AC. A right-sized solar PV system can fit on the roof area and produce enough electricity to meet annual needs.

**Integrating energy efficiency strategies into existing factory lines**

The project team evaluated the current production process of a KBS for improvements in waste and quality that could be captured to eliminate the incremental cost of the Energy Efficiency (EE) packages. These cost-offsetting strategies are crucial to achieving the goal of 50% better energy performance than code at no extra cost.

To quantify the impact of these process improvements, the team conducted a time study that captured detailed data on existing processes. We created a discrete event simulation (DES) to model the baseline factory process and compared it to various modeled scenarios to identify

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[1] "Monthly Average Retail Price of Electricity - Industrial," *NYSERDA*. **https://www.nyserda.ny.gov/Researchers-and-Policymakers/Energy-Prices/Electricity/Monthly-Avg-Electricity-Industrial** (accessed Feb. 07, 2023).

[2] "Annual Energy Prices," *NYSERDA*. **https://www.nyserda.ny.gov/Researchers-and-Policymakers/Energy-Prices/Annual-Prices** (accessed Feb. 07, 2023).

whether the time saved by reducing waste and improving quality would be enough to offset the time and costs of incorporating EE packages. After performing the comparative analysis, the team found that the proposed scenario shows a theoretical 3.8% time reduction after executing or running the simulation model for approximately 100 hours. The major learning is that new activities related to energy efficiency strategies can be added to the main production line without impacting the weekly production rate of 8 modules completed per week.

### Integrating energy efficiency strategies into existing factory QA/QC processes

Modular factories are already subject to stringent third-party monitoring for building quality. Modular construction typically has a quality enhancement program at every stage in the production process, which includes monitoring building materials and deploying quality control specialists. Modular buildings are built according to local regulations and codes where the home will be installed, similar or identical to those that apply to conventional site-built homes. A key aspect of quality control is ensuring that construction of the building matches engineered drawings.

The project team worked with KBS to develop a Zero Energy Modular (ZEM) Quality Control Protocol. The protocol provides guidance to factories constructing high-performance, zero-energy buildings. It can be used as an appendix to existing factory quality control manuals. Building off of the existing KBS QA/QC Protocol, we integrated additional steps needed to ensure that the EE components are appropriately installed so the building achieves its energy performance goals. Specifically, we provided guidance on QA/QC of high-performance envelopes, mechanical systems, duct systems, ventilation, and exhaust. We also provided relevant QA/QC program checklists to facilitate compliance with programs such as ENERGY STAR and Zero Energy Ready Homes.

# Introduction

The ZEM Construction System is a framework that approaches multifamily construction as a system through the lens of modular factories. Innovations in factory construction and process-as-product thinking support how modular building can reduce the time, money, and waste involved in construction, while building to a zero-energy standard.

The project has two aims for the factory and  building design:

1. To achieve energy performance 50 percent better than the 2018 International Energy Conservation Code (IECC); and
2. To achieve this level of energy performance at no additional cost.

## WHY MODULAR?

- **Faster** construction timeline by 30-50%
- **Higher quality**: construction occurs indoors in a controlled, standardized environment
- **Less waste**: streamlining processes can reduce material waste by more

# Background

The DOE recognizes a zero energy building as "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy."[3] This definition assumes that all cost-effective energy efficiency measures and renewable energy systems are included in the building design.  Early definitions of zero energy buildings allowed for delivered fossil fuels to be offset by site generated renewable energy. Current trends promote building electrification and eliminate all combustion of fossil fuels from building operations. This report's definition of zero energy assumes that the building has eliminated all onsite fossil fuel use and is fully electrified with onsite solar photovoltaics (PV).

Federal, state, and utility  supports that were designed to promote zero energy construction were created with onsite construction processes in mind. These include:

- Local and national building energy codes
- Energy raters from state- and utility-sponsored energy efficiency and renewable energy programs perform verification visits to construction sites. These visits can be a challenge

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[3] Common Definitions for Zero Energy Buildings. Prepared for the U.S. Department of Energy by The National Institute of Building Sciences. September 2015. **https://www.energy.gov/eere/buildings/articles/common-definition-zero-energy-buildings**

for modular buildings: modular factories often serve broad, multi-state markets and may be located in a different state than energy raters for a particular program.

- Payment schedules for public and private financing for multifamily buildings follow site-built payment timelines. The different timelines for modular factories can result in misaligned payment schedules.

In light of these challenges, our work explored how to effectively integrate long-standing and emerging strategies, tools, and techniques from the energy efficiency and decarbonization industry to the offsite construction industry using modular construction and multifamily buildings as an example. This report describes business as usual (BAU) modular construction and identifies strategic ways to embrace and integrate decarbonization techniques to build healthy, affordable, high-quality multifamily buildings.

## Why Modular?

### Time and Cost Savings

A well-coordinated modular construction system presents the opportunity to integrate energy efficiency measures into the building design and assure quality. According to *Design for Manufacturing and Assembly: Concepts, Architectures and Implementation* (DfMA), a foundational reference for engineers and designers, the operating principle of chunking or clustering helps the designer to integrate the manufacturing criteria and enables an easy assembly process.[4] This approach can be applied to the modular building process by carefully separating construction tasks into stations that cluster trades and individual building blocks/pieces, but promote the uninterrupted flow of work. The U.S. has lagged behind much of the industrialized world in off-site construction. Recent studies report that modular construction can save up to 20 percent on hard costs and reduce construction time by up to 50 percent when executed as planned.[5]

In 2018, Endzelis and Dausky reported that the clearest advantages of modular construction come from the shorter duration of construction, higher quality of work performed, and improved safety for workers.[6] These factors can be translated into financial savings (e.g., fewer defects = fewer repairs). The Modular Building Institute estimates that modular projects have 30 percent to 50 percent time savings compared to traditionally structured projects.[7] Similarly, DeLuxe Building

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[4] Molly et al. 2012. Design for Manufacturing and Assembly: Concepts, Architectures and Implementation. Springer US. DOI: 10.1007/978-1-4615-5785-2.

[5] Stein. 2016. Disruptive Development: Modular Manufacturing in Multifamily Housing: http://ternercenter.berkeley.edu/uploads/A.Stein_PR_Disruptive_Development_-_Modular_Manufacturing_in_Multifamily_Housing.pdf

[6] Endzelis and Dausky. 2018. Comparison Between Modular Building Technology and Traditional Construction. Journal of Sustainable Architecture and Civil Engineering.

[7] Modular Building Institute. 2015. Permanent Modular Construction: Process, Practice, Performance.

Systems and Gluck+ estimate that modular construction can reduce construction timelines by 50%.[8] Figure 1 compares a construction schedule and major construction phases for site-built and modular projects. In general, there are two major differences when using modular construction: 1) there is a significant overlap between module construction and site preparation phases; and 2) installation and site finishing takes considerably less time.

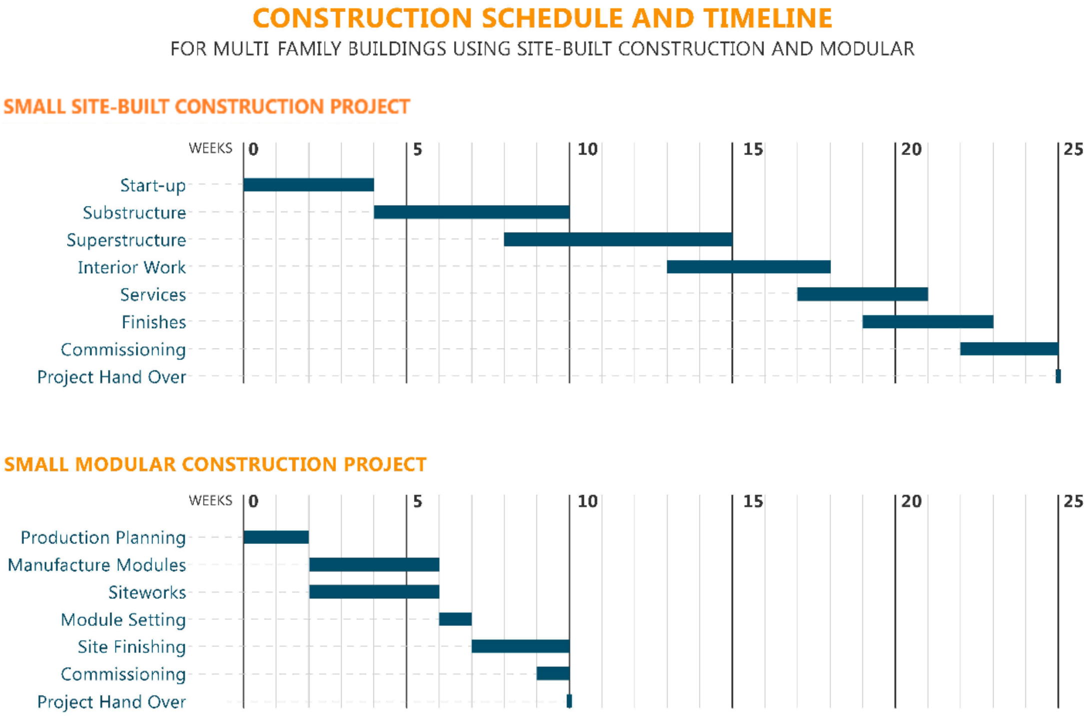

Figure 1. Construction Schedule and Timeline for Multifamily Buildings Using Site-Built Construction and Modular.[9]

The cost and time efficiencies that can be gained through modular construction depend on a well-coordinated construction timeline and team. For example, time-savings can come from building construction occurring in tandem with site and foundation development. However, if the site is not ready, these efficiencies may be lost, and the manufacturer will need to manage the storage of the units, often taking up space in the factory and thereby limiting production capacity. The timeline of modular construction can be a significant shift away from business as usual for the construction industry.

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[8] Brown, 2014. Fabulous Pre-Fab: Applying Modular Construction to Multifamily Residential Projects in Washington, DC: **https://hickokcole.com/wp-content/uploads/2016/08/FABULOUS-PRE-FAB_PRESENTATION-sm-2.pdf**.

[9] Ibid.

### Other Savings

The Modular Building Institute (2010) identified other aspects of modular construction that increase productivity, such as more controlled working conditions, fewer job-site environmental impacts, compressed project schedules, fewer conflicts in work crew scheduling, reduced requirements for onsite materials storage, and increased worker safety.[10] Another tangible savings for modular construction relates to material waste. If construction processes are well-designed, up to a 90 percent reduction in waste can be achieved in materials such as wood pallets, shrink wrap, cardboard, plasterboard, timber, concrete, bricks, and cement.[11]

One of the ways that modular construction achieves cost reductions is through bulk ordering supplies. Factories are required to purchase materials in bulk, which reduces costs. Generally, buyers can expect to pay 10 percent to 25 percent less for a prefabricated house versus a stick-built house.[12] Further cost reductions can be achieved by other factors, such as on-site overhead reduction, avoidance of weather extremes, standardization of design, high level of energy efficiency, and higher efficiency in installation.[13] Many see modular construction as the future of the building industry because it offers an advantage over conventional construction in terms of speed, quality and cost.

## Focus on Multifamily Housing Construction

Our study focuses on energy and cost performance in multifamily housing construction. Multifamily buildings are particularly relevant in cities and communities across the northern U.S. as the demand for housing grows more acute, affordable housing, in particular. An estimated 4 million affordable rental units are needed in climate zones 5 and 6 alone.[14,15] Figure 2 below illustrates that the many households in renter-occupied low-rise multifamily[16] are facing high

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[10] Modular Building Institute. 2010. Improving Construction Efficiency and Productivity with Modular Construction: **https://growthzonesitesprod.azureedge.net/wp-content/uploads/sites/2452/2021/06/Whitepaper_ImprovingConstructionEfficiency.pdf**

[11] See: www.modular.org/marketing/documents/WRAP_ ModernMethodsConstruction_Report.pdf

[12] Cartwright. 2011. Zoning and Designing for Affordability Using Modular Housing: Iowa State University.

[13] Kamali and Hewage. 2016. Life cycle performance of modular buildings: A critical review. Renewable and sustainable energy reviews.

[14] The Building America definition of cold climate is a region with between 5,400 and 9,000 heating degree days (65˚F basis), this corresponds to IECC climate zones 5 and 6: https://www.energy.gov/eere/buildings/climate-zones

[15] The National Low Income Housing Coalition reports on the number of affordable and available rental units by state for extremely low income renters. Extremely low income households are those with incomes at or below either the federal poverty guideline or 30% of their area median income, whichever is greater. National Low Income Housing Coalition. 2020. The Gap: A shortage of affordable rental homes: **https://reports.nlihc.org/gap.**

[16] Multifamily low rise is defined here as multifamily buildings with 3 to 49 units.

energy burdens, the percentage of household income spend on energy.[17] The multifamily building sector is one of the fastest growing within the construction industry; in 2018 the U.S. Census and Department of Housing and Urban Development (HUD) reported the construction of 345,000 new units and 12,000 new buildings [18] A key goal of this work is to develop a construction system that can quickly add efficient, high-quality, low-rise multifamily buildings to the housing market.

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[17] Data obtained from the U.S. DOE Low-Income Energy Affordability Data (LEAD) Tool: https://www.energy.gov/eere/slsc/maps/lead-tool.

[18] U.S. Census and HUD: Survey of Construction: **https://www.census.gov/econ/overview/co0400.html**

# Components of a ZEM Construction System

The goal of the ZEM Construction System is to leverage modular construction to build all-electric, high-performance multifamily buildings quickly and cost-effectively. The project team and industry partners identified four key components that make up the ZEM Construction System that contribute to construction cost savings and promote zero energy multifamily buildings.

1. Modular Factory: the modular factory of the future is efficient in its processes and comfortable for workers.

- Factory Building: all-electric and zero energy, with above-code roof and wall insulation, HVAC system, and PV solar array. Our modeling shows that the operating costs of this factory design are lower than those of an equivalent factory heated with natural gas and lacking a ventilation system.
- Factory layout and processes are specialized for the construction of high-performance multifamily buildings. Many stations are similar to a traditional modular factory, but there are also specialized workstations devoted to HVAC installation, envelope installation, air sealing and solar PV installation.
- Factory production: to reduce line changes, and increase productivity, only one type of building is constructed to the same high-efficiency standard– in this case an all-electric, zero energy multifamily building.

2. Multifamily Building: the building design is unitized, which allows most of the construction to happen in the factory. Typical modular construction is 80% factory built and 20% finished on site. Maximizing work in the factory reduces handoffs between trades and leverages the factory QA/QC process which can reduce costs.

- Each apartment is contained within a single volumetric unit.
- Building Envelope: superior quality insulation that is installed in the factory.
- Mechanical Equipment: a key aspect of all HVAC is assembled in a mechanicalpod that is installed in the factory, with off-the-shelf equipment for heating, cooling, ventilation, hot water, and batteries if included in the unit design.
- Ducting Strategies: optimize and streamline ducting layout for interfacing air systems and envelope as well as refrigerant line routing from the outdoor unit to eliminate mateline penetrations.
- Solar and Storage: a modular roof system that enables the ease of installation of solar PV panels in the factory while also allowing final on-site water-tight connections to be made between modules.

3. Modeling: there are two key modeling approaches in the ZEM Construction System.

- Building Energy Modeling (BEM): we used building energy modeling to guide building and unit design and explore different pathways to meet the project's energy performance goals.

- Discrete Event Simulation (DES): DES can be used to optimize factory processes and assess the impact and value of any proposed changes. We used DES to explore how the EE packages could be integrated into the processes of an existing modular factory.

4. Monitoring: monitoring provides a feedback loop to modeling assumptions. In this document, we provide guidance on monitoring during the factory construction process and post-occupancy monitoring:

- QA/QC protocols: monitoring factory performance is especially critical when integrating energy strategies into the home design to ensure proper execution to achieve energy performance. We developed an example QA/QC factory protocol that integrates QA/QC of EE measures and meets the requirements of EE programs such as DOE's Zero Energy Ready Home (ZERH).

- Post-occupancy monitoring: monitoring units post-occupancy is one of the only ways to assess energy performance and the accuracy of the initial energy modeling. In this blueprint we provide an overview of post-occupancy monitoring methods and best practices.

# Case Study: ZEM Multifamily Building Design

## Summary

The project team worked with Solar Home Factory (SHF), a vertically integrated modular factory owner and developer based in Geneva, New York. In 2020, SHF was in the process of designing both a new, expanded factory, and a new multifamily building design. The project team collaborated with SHF on both of these initiatives (see Appendix A for proposed ZEM factory layout).

In this section we will describe:

- The key design objectives of the ZEM multifamily building;

- Example of a building floor plan that implements the design objectives;

- Example of a multifamily unit design.

## Key design objectives and processes

Energy efficiency and green building design elements must be considered prior to solar + storage deployment. Beyond code new construction programs such as PHIUS and Zero Energy Ready Homes provide cost optimized design guidelines for envelope, all-electric HVAC and appliance specifications. There is a trend among modular home companies to design for increased energy efficiency, incorporating green design building principles and actively working to reduce waste in projects. More recently, some modular builders are moving beyond a focus on all-electric high-performance construction, incorporating energy generation and battery storage into their designs as well. As states, cities, and utilities continue to set decarbonization and climate goals, the ability of modular new construction to address energy efficiency, curb energy demand, and offer less wasteful construction options becomes more valuable.

Maximize factory construction: Business as usual modular is approximately 80% of the building constructed in the factory and 20% of construction is finished on site. By increasing the percent of construction in the factory, there is an opportunity to eliminate rework by reducing handoffs between trades, and increase labor efficiencies by completing the majority of the work in the factory.

Modularize building design: To support maximizing factory construction, product design will require 'modularization' with the prime opportunities being apartment units and HVAC systems, using standardized off-the-shelf components that do not require custom project-by-project design, engineering, product customization, and non-standardized approval process.

For high-performance envelope:

- Design for high-performance optimized thermal control that eliminates thermal bridging that can be installed in the factory, as opposed to traditional continuous exterior insulation applied on-site. The envelope assembly can be combined with continuous insulation as part of the sheathing system and can also be built into structural insulated panels.
- Improving airtightness through attention to connections and air sealing with an ionized sealant added through a controlled spraying process.
- Design with QA/QC tools and methods (such as nondestructive testing) to achieve a factory-installed airtight envelope. This includes designing a dedicated factory station or bay to perform ionized sealant process. An integrated design process would include planning for a QA/QC envelope design review.

For HVAC equipment:

- Design an HVAC pod with off-the-shelf equipment for space heating, cooling, ventilation, and domestic hot water along with advanced control systems for pre-assembly as a "skid" in the factory. Components include a set of all-electric heat pump mechanical equipment with integrated functionalities through built-in controls, with heating, cooling, hot water, ventilation (including energy recovery), electrical management, and battery storage within a single package. Incorporate design for manufacturing and assembly principles for build-to-stock of subsystems through chunking and prefabrication for volume production in production lines.

- Contain ducts for air systems and refrigerant lines within apartment to eliminate mateline penetrations. This includes design for optimized air flow and unitized air system for each apartment. A fully ducted mid-static heat pump integrated with a recovery ventilator can satisfy thermal loads, maintain acceptable humidity levels, and ensure optimal indoor air quality through high quality distribution and filtration. Designing the ducted return and filter combination to be a common, standard size will increase the likelihood that the system will be relatively easy and cost-effective to maintain.

For solar + storage:

- Design a modular roof system that enables ease of installation of solar PV panels in the factory while also allowing final on-site water-tight connections to be made between modules.
- Design the electrical distribution system to be easily completed on-site with simple final tie-ins to central meter or to in-unit electrical panels. Install in-unit battery systems for critical load panel in the factory.
- Streamline design code review with factory inspection for solar + storage, eliminating on-site factory inspections and approvals.

## Floor Plan Layout

The project team and industry partners created an example floor plan that incorporates the ZEM construction system design objectives.

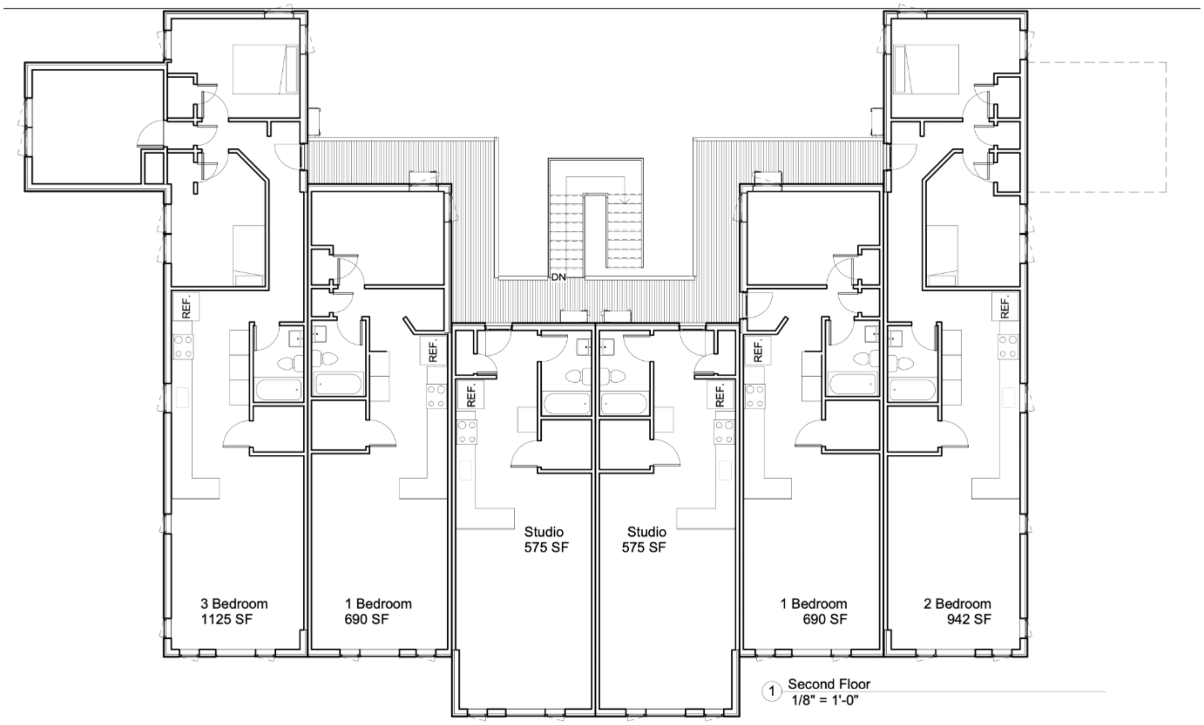

Figure 2. Floor Plan Layout for a Modular Multifamily Building Design.

The following are the key design characteristics of the floor plan layout (as shown in Figure 5 below):

- An apartment (programmatically) is contained within a single volumetric module (spatially). For example, a 2-bedroom apartment is contained within a single volumetric module of 1,125 square feet, instead of sharing the programmatic design across two-three modules spatially. This eliminates module-module mateline penetrations and produces a 2-bedroom apartment to leverage productivity efficiencies to be gained during the repeatable construction process in the factory.

- Three typologies of volumetric modules (by dimensions) reduce the number of variabilities in the volumetric modules in the factory production line. This brings more certainty to the production process. The factory can effectively sequence the three typologies and develop a construction schedule for the factory.

- Eliminate the need for module-module mateline penetrations for ducting by unitizing the mechanical systems both programmatically in one apartment and spatially in one volumetric module.

- Eliminate the need for module-module mateline penetrations for refrigerant line runs by strategically locating the outdoor unit in the hallway section that is part of the apartment/module that the outdoor unit will be serving.

- Strategically locating the energy exchange pod in each apartment/module to minimize supply and exhaust ducts as well as hot water distribution.
- Prefabricate sections of hallway and stairs for easy installation and integration on site.

## Mechanical Pod

The project team and SHF, evaluated the pros and cons of a centralized mechanical system, compared to a unitized mechanical pod. Use of mechanical pods would be a decentralized or unitized approach to hot water: under this approach, the hot water system would be installed in the factory. In contrast, a centralized system that would serve the entire building (or at least multiple units) and be installed on-site. Each approach presents opportunities and challenges (Table 1).

Table 1. Comparison of Centralized Hot Water and Unitized Hot Water Systems.

| | **Centralized Hot Water** | **Decentralized System, Factory-Installed** |
|---|---|---|
| **Commodification, off-the-shelf** | Large central heat pump systems are custom engineered and installed by specialist, with larger custom designed infrastructure | Off the shelf residential HVAC equipment can be sized and packaged into a "pod" for each apartment unit. |
| **Back-up** | When a central system goes down, multiple apartment units are without hot water. | If a decentralized system fails, only one apartment is without hot water. |
| **Location** | The central hot water systems with long pipe runs can be costly to install, and operate due to heat loss when water is pumped throughout the building | Decentralized hot water systems take up space in the apartment unit, |
| **Maintenance** | Central systems are easier to maintain | Decentralized hot water units, require individual maintenance and service plans to prevent simultaneous failure at the end of the equipment useful life. |

A mechanical pod contains each unit's hot water, heating, cooling, fresh air and battery systems. The washer and dryer can be included in the pod (Figure 6).

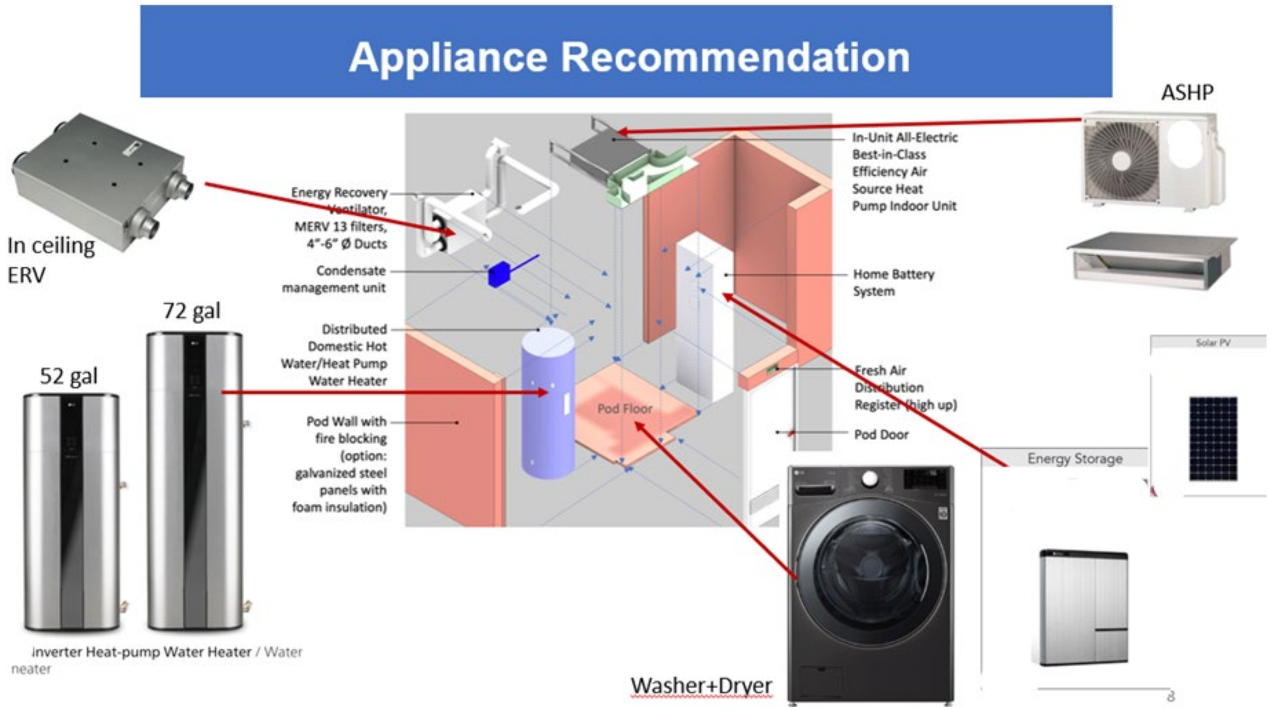

Figure 3. Idealized ZEM Unit Mechanical Pod Appliance Recommendations.[19]

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[19] Image adapted from The Energy in Modular (EMOD) Buildings Method, NREL (2022).

## Solar plus Storage

The project team worked with SHF to unitize the solar + storage systems (Figure 7). We developed a comparative analysis to understand the pros and cons of Centralized Indoor/Outdoor Battery (Site-Installed) and Decentralized System (Factory-Installed), as shown in Table 2. In summary, there are significant benefits from a decentralized system such as smaller distributed residential batteries in every apartment. Such a system maximizes work done in the factory – a ZEM best practice.

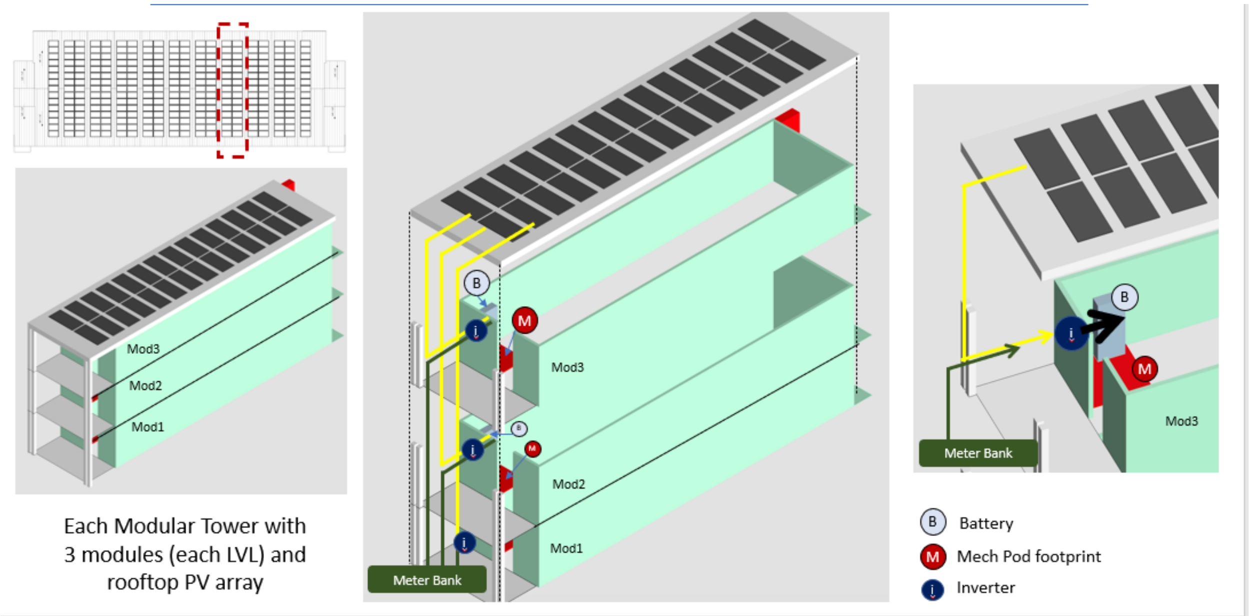

Figure 4. Unitized Solar + Storage System, Vertical-Mod-Tower Strategy[20].

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[20] The Energy in Modular (EMOD) Buildings Method, NREL (2022).

Table 2. Pros and Cons of Centralized Indoor/Outdoor Battery (Site-Installed) and Decentralized System (Factory-Installed).

| | Centralized Indoor/Outdoor Battery, Site-Installed | Decentralized System, Factory-Installed |
|---|---|---|
| **Fire Codes** | Concerns with large central indoor battery | Less concern, less infrastructure and approvals needed in the decentralized system such as smaller distributed residential batteries |
| **Commodification, off-the-shelf** | Large central systems are custom engineered and installed by specialist, with larger custom designed infrastructure (like fire protection and cooling) required | Residential batteries are pre-engineered and commodity systems manufactured at scale that can be installed by solar installers/electricians. A modular and repeatable design approach to solar and storage suggest similar cost savings as other factory installed modular systems |
| **Back-up allocation** | Central storage can be used for easier backup of house/life safety loads like egress lighting and elevators | Decentralized storage can more easily be wired to provide backup power in apartments |
| **Location** | Central storage systems can be located outside of the building in a dedicated space/power room, saving space in the apartment | Smaller distributed residential batteries located inside the apartment |
| **Approval process by authorities, code officials on design and inspection** | Questions on 'who does what' on approvals with design and inspection when work is on site | Contiguous/sequential/integrated approval process in the factory on design and inspection |

SHF’s original goal was to create a vertically integrated modular factory and multifamily development venture, but neither the new factory nor multifamily building were ultimately completed. Factory start up is a capital-intensive activity that comes with high risk from the perspective of lenders. There’s often a long lag time from getting a factory up and running to a full pipeline operating at the capacity needed to generate revenue to carry the debt. Typical multifamily construction financing and insurance products are created to match site-built payment schedules and construction types. SHF, like many modular startups, was not able to overcome the barriers created by the perceived risk of modular construction and lack of financing to launch their business.

# Case Study: Multifamily Building Specifications 50% better than Code at no extra cost

## Introduction

The project team used building energy modeling and cost modeling to design a multifamily building that meets the project goal of energy performance 50% better than 2018 IECC at no additional upfront cost. These energy performance and cost goals were developed by the ABC initiative of the DOE's Building Technology Office. The project team partnered with KBS Builders, Inc (KBS) on this modeling exercise. KBS is a modular factory located in South Paris, Maine that works closely with developers, general contractors, architects, and builders to customize and produce single and multifamily buildings.

Achieving these energy performance and cost goals would help increase adoption of all-electric and highly efficient modular construction, as well as optimize integration of energy efficiency measures into construction processes and maximize time and cost savings relative to site-built, multifamily developments. Through maximization of energy efficiency in off-site construction, the industry can move towards large-scale zero energy modular housing.

**GOAL**: a multifamily building design that achieve 50% better energy performance at no additional upfront cost.

**METHODS**: we ran 50,000 energy modeling scenarios in Open Studio to develop three energy efficiency packages: one that focused on efficient mechanical systems, one that focused on improved envelope, and one that included elements of both efficiency mechanical systems and improved envelope. We performed cost modeling in Excel using a combination of published data and detailed cost data on materials, labor, and overhead provided by our modular factory partner.

**RESULTS**: Our three energy efficiency prescriptive packages achieved 50% better energy performance. Our modeling showed that the zero energy modular multifamily costs more than the baseline scenario (11-14%), but the energy efficiency packages were a small part of overall project cost (3-6%)

# Building Energy Modeling

This section describes:

- Methods and approach used for the project's building energy modeling
- Modeling results
- Prescriptive energy efficiency packages developed for cost modeling

## Methods and Approach

Building Energy Modeling (BEM) is a critical tool used by the design and construction industry. BEM is a physics-based simulation of energy use in a building. BEM can utilize a range of building inputs, from very simplified inputs to highly detailed inputs, to provide feedback about the predicted energy performance of the building. Multifamily buildings pose unique modeling challenges because the buildings often include common spaces and can have both shared commercial and individual residential mechanical systems and equipment. In this case study, because the prototype multifamily building will be no more than three stories, it must comply with the envelope requirements of the *residential* building code. Additionally, the prototype models are assumed to contain unitized mechanical system packages; no shared equipment is assumed.

For this case study, the project team performed preliminary modeling in REM/Rate™, an industry standard residential energy modeling and code compliance software accredited by Residential Energy Services Network (RESNET). REM/Rate™ generated preliminary prototype energy models of the target unit and the 2018 IECC compliant baseline unit. These preliminary models informed assembly and mechanical efficiency target values for use with the workflow described below. REM/Rate ™ also generated effective assembly R-values utilized for HPXML inputs in the prototype models.

Following preliminary modeling in REM/Rate™, the team performed building energy modeling in OpenStudio® (OS) and utilized the NREL developed OpenStudio-HPXML (OS-HPXML) workflow. HPXML is comprised of two open data standards for describing residential buildings and transferring that data across systems. The OS-HPXML workflow generates an HPXML file which is then translated to an Open Studio Model (OSM), upon which an EnergyPlus simulation is run that utilizes the open data standard for describing residential buildings. OpenStudio is the preferred BEM platform because of its open-source nature and its unique capabilities to run large-scale BEM parametric analyses and optimization routines.

The project team's modeling consisted of a prototype baseline model that meets the minimum requirements of 2018 IECC, and iterative target models that strived to reach the goal of 50 percent more efficient than the 2018 IECC (Table 3). The baseline scenario assumes two mechanical equipment scenarios, both modeled to federal minimum efficiency levels: air-source heat pump representing an all-electric baseline scenario, and conventional gas furnace representing a more common or typical baseline scenario.  We processed OpenStudio modeling results in Microsoft Power BI to understand which measures had the most impact on overall performance.

Table 3. Baseline and Target Scenarios.

| | **Baseline Scenario** | **Target Scenario** |
|---|---|---|
| **Construction Method** | Site-built | Modular |
| **Energy Performance** | 2018 IECC Compliant | 50% better than 2018 IECC |

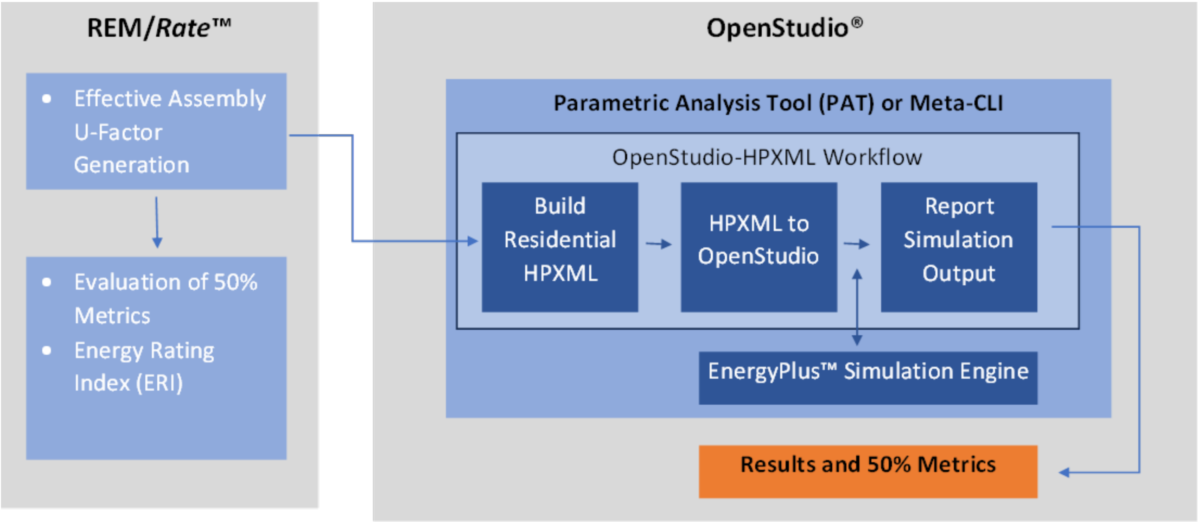


Figure 5. Energy Modeling Tools and Approach.

To conduct energy modeling of the multifamily building, the project team generated prototype units (Figure 9).  The building was assumed to be a three-story building with a central corridor comprised of 24 one- and two-bedroom units. No common spaces were assumed. The prototype units were modeled at each of the vertical and horizontal positions within the building.  Whole building energy was calculated by summing the individual unit energy for each location.

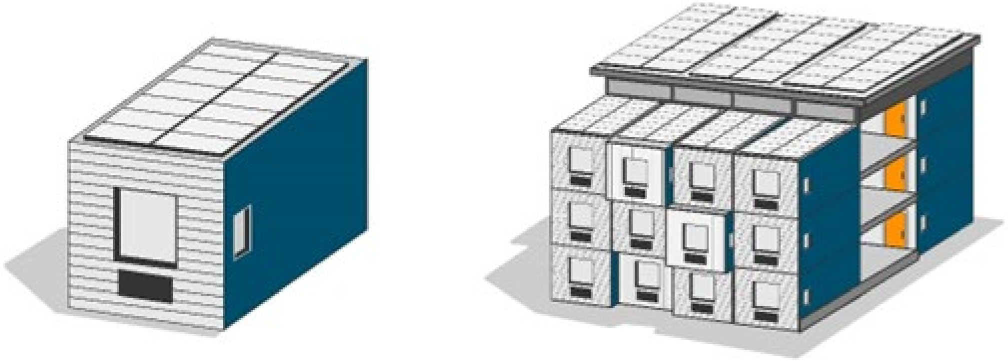


Figure 6. Prototype Modular Multifamily Unit and Building Design.

We limited energy modeling to cold climate regions using Building America's definition of cold climate: approximately 5,400 heating degree days (65°F basis) or more and fewer than approximately 9,000 heating degree days (65°F basis). The Building America cold climate region generally corresponds to IECC climate zones 5 and 6.

## Energy Modeling Results

### Energy Efficiency Package Development

The project team's energy modeling confirmed that it is possible to achieve a 50% reduction in energy use relative to 2018 IECC. We developed three prescriptive packages that met the project goal of 50% better energy performance relative to a baseline of 2018 IECC compliance. Simulations included approximately 50,000 variations on air tightness, insulation levels for wall, floor and roof, and mechanical system efficiencies.

Figure 10 shows the average results from all parametric runs for a gas heat baseline, electric heat baseline, and target scenarios. The graphic shows that, when looking at total site energy, the target scenario exceeds the 50% goal with 60% potential savings over 2018 IECC gas heat baseline. If we assume the baseline is electric heat, the target scenario achieves 39% savings. However, when looking at $CO_2$ emissions, the target scenarios fall short of the 50% goal, achieving about a 30-40% reduction for electric and gas baselines respectively. This is due, in part, to the use of a national average emission factor in calculating $CO_2$ emissions. As electricity grids become cleaner, the percent savings for our all-electric target scenario will increase relative to a fossil fuel baseline.

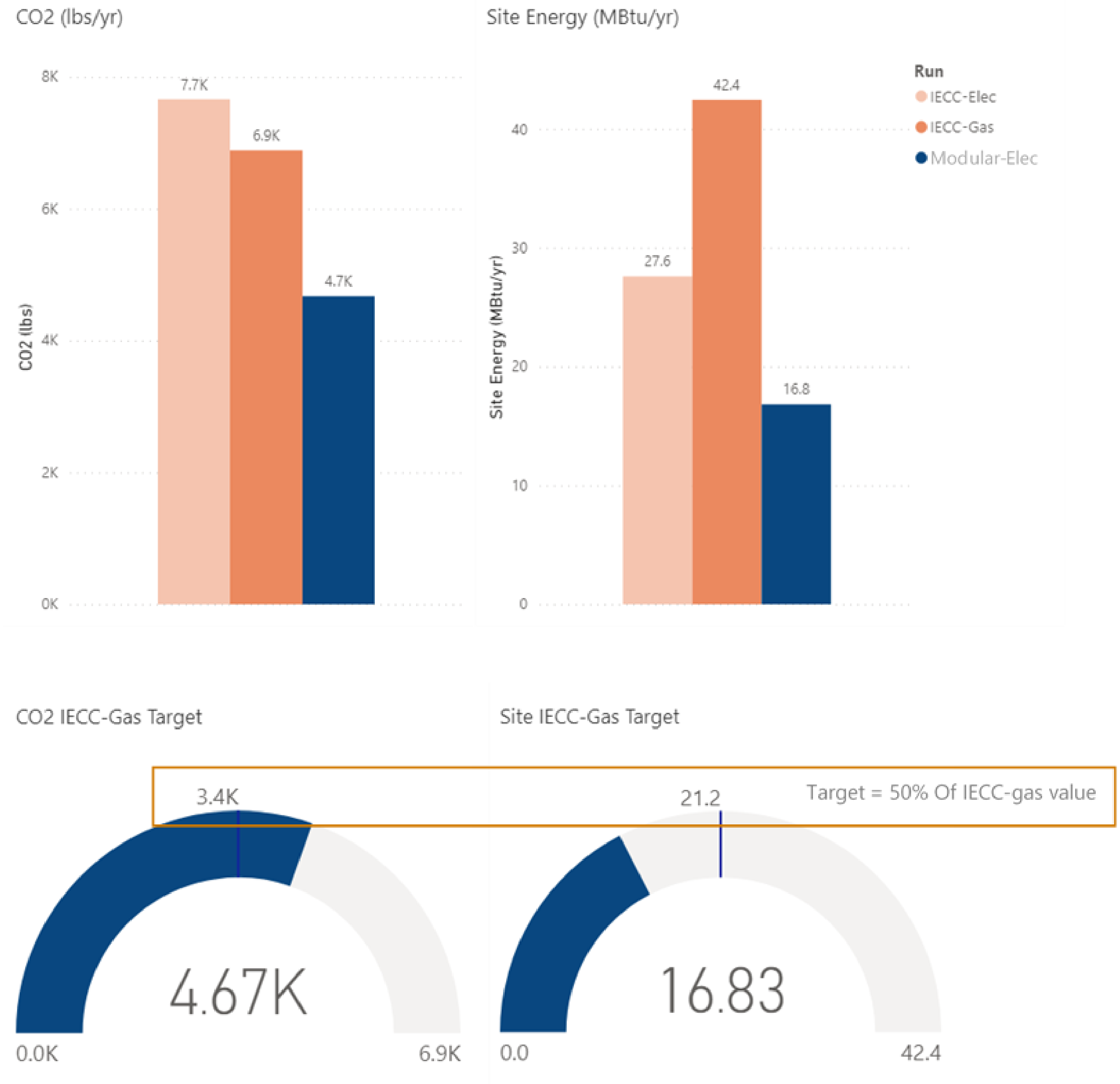
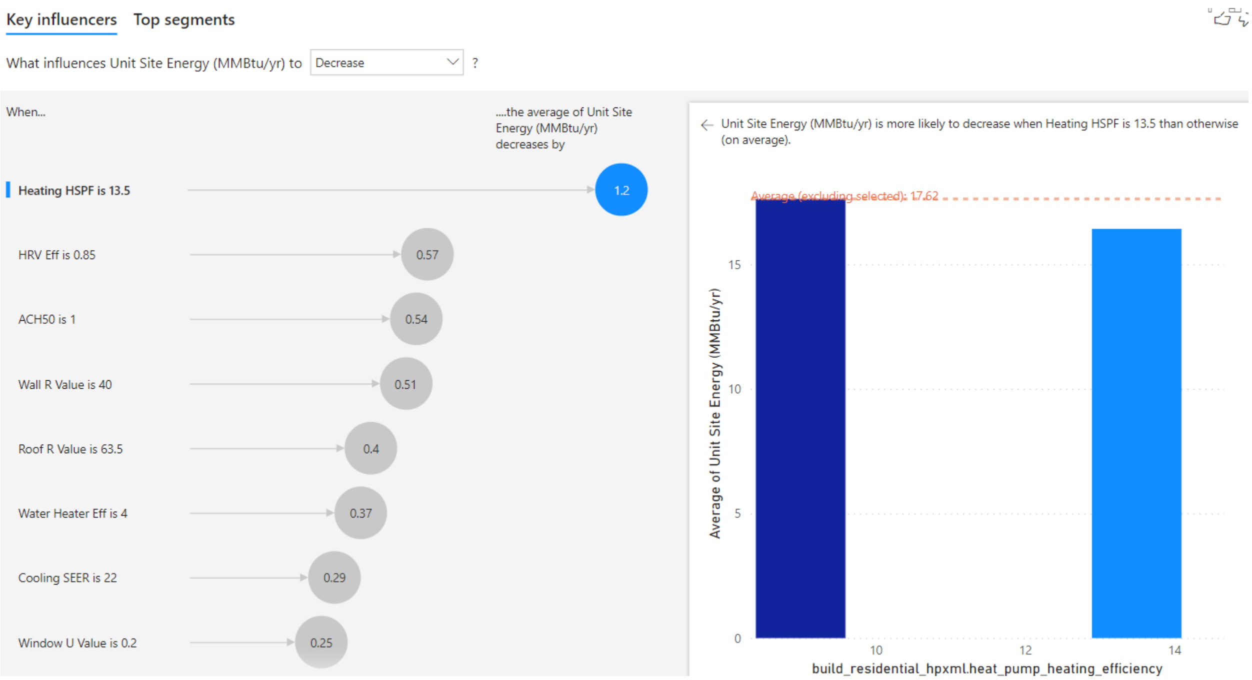


Figure 7. OpenStudio Parametric Analysis Tool Summary Results.

After reviewing the potential energy reductions overall, the modeling team analyzed which variables had the greatest impact on energy reduction utilizing Power BI’s ‘Key Influencer’ visualization. The key influencer’s function allows the user to easily see which factors, or variables, most influence the targeted outcome. Out of approximately 2,000 variations simulated, Power BI identified eight key influencers. The top eight influencers on unit energy use, in order of greatest to lowest impact, were: heat pump heating efficiency, HRV efficiency, air leakage, wall assembly R-value, roof assembly R-value, heat pump water heater efficiency, heat pump cooling efficiency, and window U-factor.  Heat pump heating efficiency values had the greatest impact on site energy reduction over the other key influencer variables.

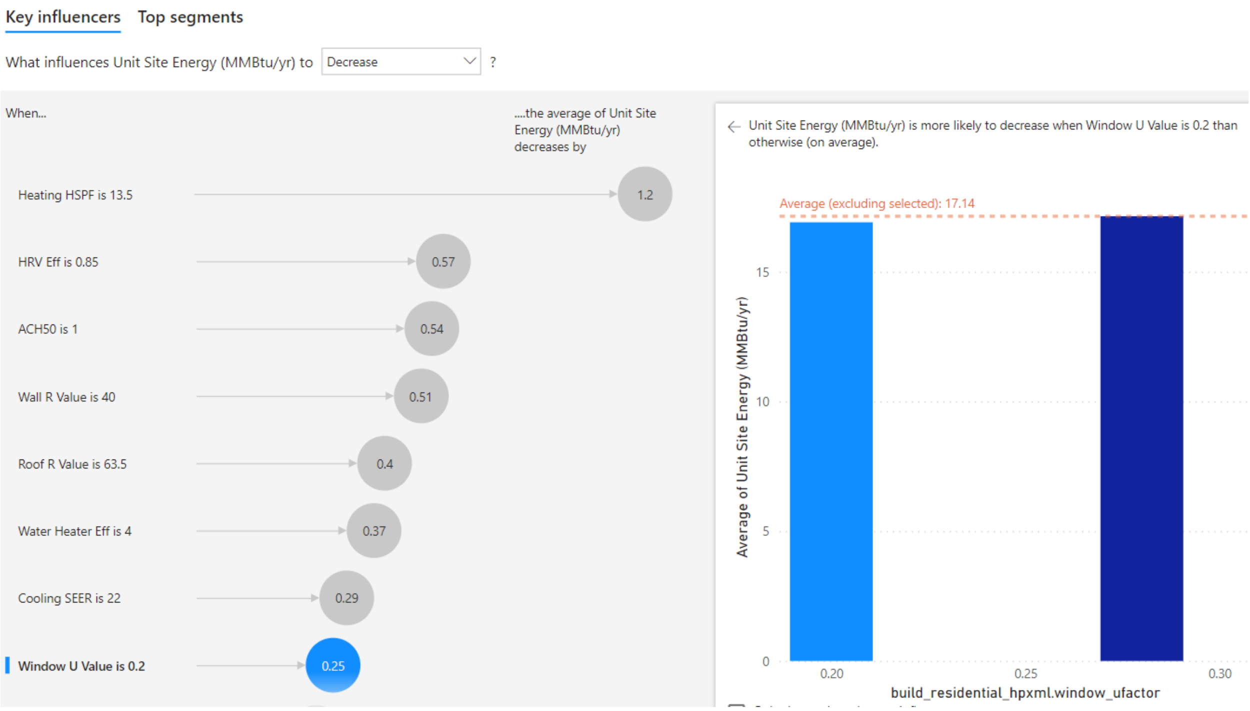
Figures 11 and 12 illustrate the impact on total annual site energy for heat pump heating efficiency and window U-factor, the top and bottom key influencers identified by Power BI. Across all target efficiency scenarios, annual site energy use was reduced by 1.2 MMBtu on average when the heat pump heating efficiency variable was set to 13.5 HSPF (light blue bar on right) vs. 9 HSPF (dark blue bar on left). Meaning, of all key influencers, heat pump heating efficiency has the greatest impact regardless of remaining efficiency variables. By contrast, stepping down from a U-0.28 to a U-0.20 window achieves 0.25 MMBtu savings annually across all efficiency scenarios. For a 96-unit multifamily building, the impact of installing a 13.5 HSPF heat pump vs. a 9 HSPF heat pump equates to almost 34,000 kWh per year, or a ~30 kW south-facing solar PV array in a northern climate. Installation of windows with a U-factor of 0.20 vs. 0.28 has the potential to further reduce energy consumption by just over 7,000 kWh per year, or an additional ~7 kW of PV.


What influences Unit Site Energy (MMBtu/yr) to Decrease ?

Unit Site Energy (MMBtu/yr) is more likely to decrease when Heating HSPF is 13.5 than otherwise (on average).

Figure 8. Power BI Key Influencers: Heat Pump Heating Efficiency Impact on Annual Site Energy.

Across all eight key influencers, the number of thermal envelope and mechanical system efficiency improvements were equally split. However, the potential energy reductions achievable by mechanical system improvements, largely driven by heat pump heating efficiency, were about 45% higher than for thermal envelope improvements. These results are illustrated in Figure 13.



What influences Unit Site Energy (MMBtu/yr) to Decrease ?

| When... | ....the average of Unit Site Energy (MMBtu/yr) decreases by |
|---|---|
| Heating HSPF is 13.5 | 1.2 |
| HRV Eff is 0.85 | 0.57 |
| ACH50 is 1 | 0.54 |
| Wall R Value is 40 | 0.51 |
| Roof R Value is 63.5 | 0.4 |
| Water Heater Eff is 4 | 0.37 |
| Cooling SEER is 22 | 0.29 |
| **Window U Value is 0.2** | 0.25 |

Unit Site Energy (MMBtu/yr) is more likely to decrease when Window U Value is 0.2 than otherwise (on average).

Figure 9. Power BI Key Influencers: Window U-factor Impact on Annual Site Energy.

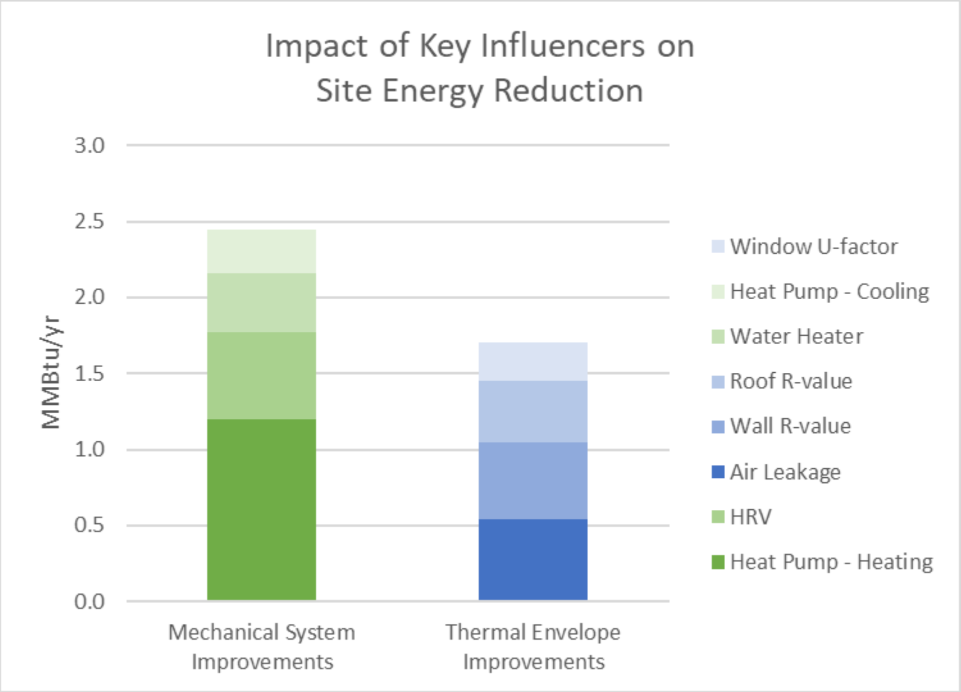


Figure 10. Key Influencers Impact on Site Energy Reduction.

Using the results from the parametric analysis, the modeling team developed two target energy efficiency packages. Parsing the aggregate results to isolate envelope only improvements and mechanical only improvements, the results showed that the 50% target could be reached, and exceeded, by either maximizing the envelope efficiency values while maintaining federal minimum standard equipment efficiency values, or by maximizing mechanical system efficiencies and maintaining 2018 IECC envelope requirements. This is shown in the half doughnut charts at the bottom of Figure 14.

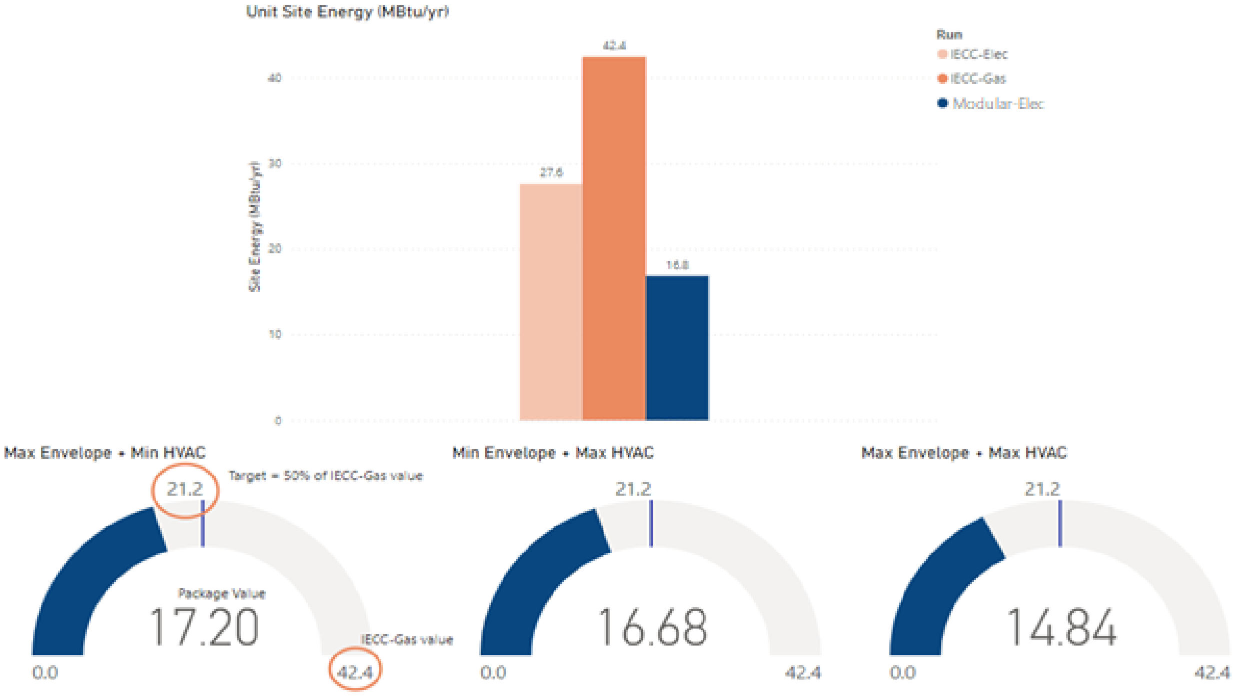


Figure 11. Energy Efficiency Package Results Relative to the 50% of 2018 IECC Target.

The results above use total site energy as the metric with a gas heat baseline. While the residential 2018 IECC defines our baseline energy performance, it does not specify minimum mechanical system efficiencies, and the project team agreed that total site energy is the best metric to base our analysis on. Total site energy is inclusive of all aspects of the building that impact energy consumption. By focusing our target goals on total site energy we will be able to attain significant reductions in energy use and related impacts such as homeowner costs and emissions. A fossil fuel baseline is the most common heating fuel in multifamily buildings, especially in cold climates. The remainder of this report will assume a gas heat baseline and total site energy when discussing the target energy reduction.

## Energy Efficiency Package Components

Based on results of the parametric analysis, and review of the KBS factory process, our modular factory partner, we developed energy-efficiency specifications for two high performance packages for costing. The target packages take different approaches to meet the energy goal, one focusing on a high-performance thermal envelope, the other focusing on high performance mechanical equipment. These two packages were generated, in part, because the goal of the project was to demonstrate energy savings relative to the IECC baseline. The IECC does not regulate energy efficiency of mechanical equipment such as heating, cooling, hot water, nor of appliances. However, the project team wanted to demonstrate that the 50% energy reduction could also be met by focusing on system upgrades, and potentially at lower costs. Additionally, electrification with high efficiency heat pump technologies supports long term decarbonization efforts. Both packages assume ENRGY STAR® appliances and 100% LED lighting. Table 4 provides a summary of the envelope and equipment efficiencies for the two target packages. The R-values presented here are nominal insulation R-values.

Table 4. Prescriptive Packages Developed for Incremental Costing over Baseline Construction.

| **Assembly/System** | **Package 1**<br>*(Code Envelope with High Performance Mechanicals)* | **Package 2**<br>*(High Performance Envelope with Federal Minimum Mechanicals)* |
|---|---|---|
| **Thermal Envelope** | | |
| Frame Floor | R-30 | R-40 |
| Ceiling/Roof | R-49 | R-60 |
| Above Grade Walls | R-20 | R-30 |
| Windows | U-0.30 | U-0.22 |
| Air tightness | 3 ACH50 | 1 ACH50 |
| **Mechanical Systems** | | |
| Heating | 13.5 HSPF<br>Cold Climate Heat Pump | 8.2 HSPF<br>Air Source Heat Pump |
| Cooling | 22 SEER<br>Cold Climate Heat Pump | 14 SEER<br>Air Source Heat Pump |
| Hot Water | 4.0 EF<br>Heat Pump Water Heater | 0.92 EF<br>Electric Storage Tank |
| Ventilation | 0.75 SRE<br>Heat Recovery Ventilator | 0.60 SRE<br>Heat Recovery Ventilator |
| Ducts | Inside conditioned space | |
| **Lighting & Appliances** | | |
| Lighting | 100% LED | 100% LED |
| Appliances | ENERGY STAR | ENERGY STAR |

Additionally, a third EE package was created that combines the high-performance envelope with high performance mechanical systems. Each of these high-performance packages were compared against the baseline model (2018 Residential IECC thermal envelope efficiencies and Federal Minimum Standard mechanical system and appliance efficiencies not governed by IECC due to federal preemption).

Table 5. Efficiency Specification Inputs for the Baseline Models.

| **Thermal Envelope** | | |
|---|---|---|
| **Assembly** | **Climate Zone 5** | **Climate Zone 6** |
| Frame Floor | R-30 (U-0.033) | |
| Ceiling/Roof | R-49 (U-0.026) | |
| Above Grade Walls | R-20 (U-0.060) | R-20+5 (U-0.045) |
| Windows | U-0.30 | |
| Infiltration | ACH50 3.0 | |
| **Mechanical Systems** | | |
| **System** | ***Gas Heat*** | |
| Heating | 80 AFUE<br>Natural Gas Furnace | |
| Cooling | 13 SEER<br>Central Air | |
| Ventilation | Exhaust Only Ventilator<br>2018 IECC minimum fan efficacy | |
| Ducts | Inside conditioned space | |
| **Lighting & Appliances** | | |
| Lighting | 90% CFL / 10% Incandescent | |
| Appliances | Conventional | |

## Energy Performance

A critical factor in determining achievement of the “50% goal” lies in the metric(s) chosen to demonstrate energy performance improvement. IECC governs the energy performance of the thermal envelope, air leakage, lighting efficacy, and certain aspects of HVAC and hot water equipment. However, IECC does not currently require minimum efficiency specifications for heating, cooling and hot water systems, or for appliances, as it does for the thermal envelope. Our modeling does take into account all aspects of a building that impact energy use, whether or not they are governed by IECC. As discussed in the previous section, the project team ultimately focused on total annual site energy as the basis for meeting our target. Figure 15 shows the potential estimated savings for multiple metrics, for each target package over a gas heat baseline. All packages nearly meet or exceed the 50% target.

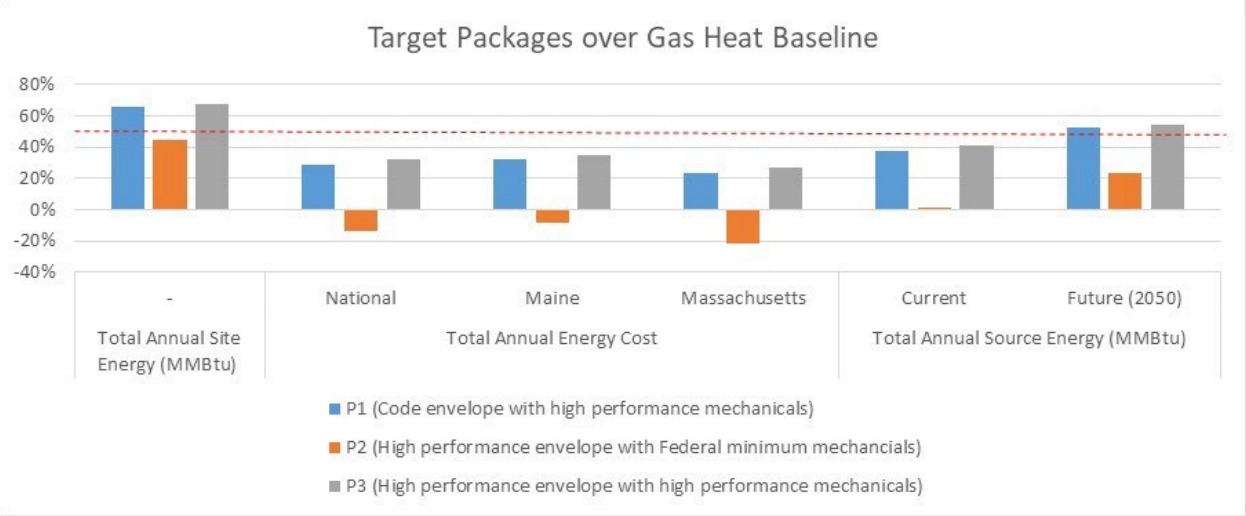


Figure 12. Estimated Target Package Savings Over Natural Gas Heat Baseline.

# ZEM Multifamily Building Cost Model

This section describes out approach to modeling ZEM multifamily building construction costs and covers:

- Cost modeling methods and approach
- Site-built cost assumptions
- Factory cost assumptions
- Cost modeling results

## Methods and Approach

We developed a cost model to compare construction costs of the 2018 IECC baseline site-built building with a factory-built building that meets our energy performance goal, integrating the output of the building energy modeling described above with a cost estimation spreadsheet.

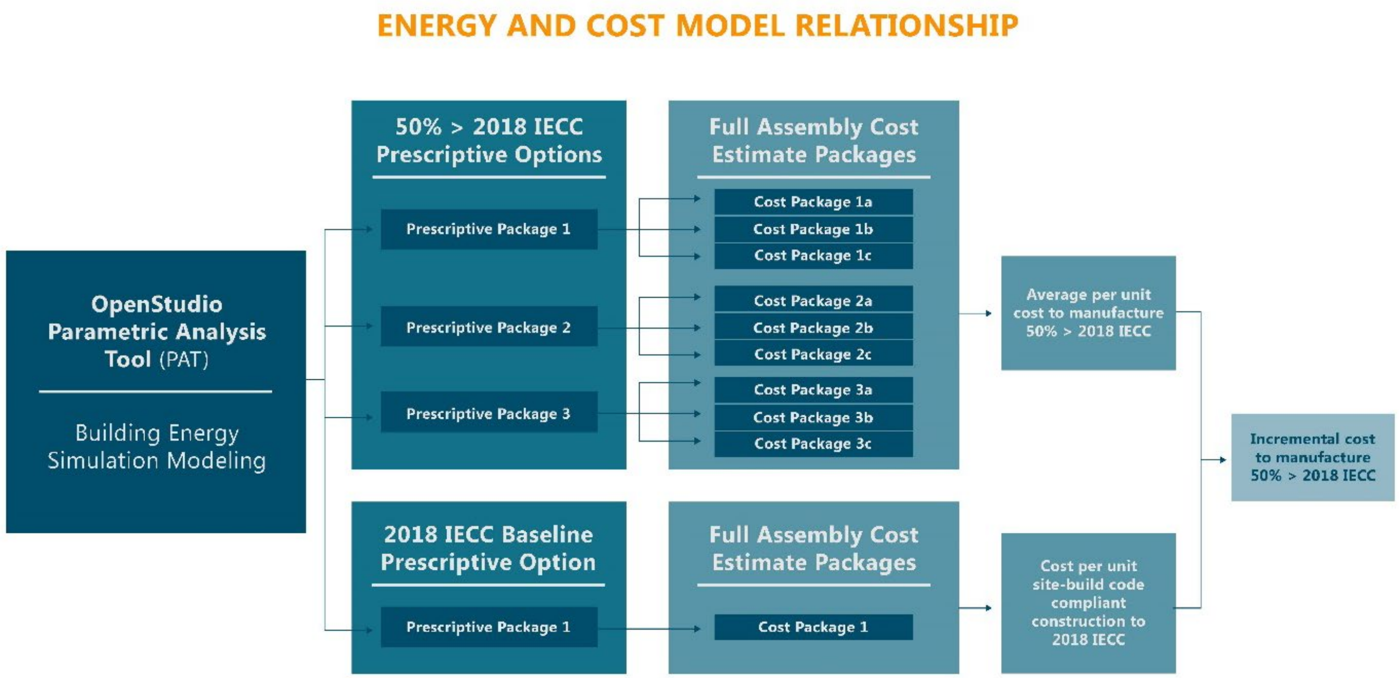


Figure 13. Energy and Cost Model Approach and Integration.

Broadly, our cost model divides total cost into key sub-cost categories that will be examined in a sensitivity analysis to test the influence assumptions and variables have on total cost (Table 6). In addition to comparing baseline site-built costs to ones that meets the energy efficiency goals, the results of the sensitivity analysis will guide the factory data collection, and detailed bottom-up analysis of labor, material, waste, and quality comparing a site-built, code compliant baseline with a modular 50% better than code target building. Ultimately, a key goal of this project is to use the cost model to analyze the construction process in an existing factory and to design a modular factory optimized to build energy efficient units.

Table 6. Cost Model Components.

| | | |
|---|---|---|
| **Factory Costs**<br>**Site Costs** | Material Cost | Direct Material Cost |
| | | Material Waste |
| | Labor Cost | Direct Labor Cost |
| | | Quality Labor Cost |
| | Overhead | Facilities and Equipment |
| | | Indirect Operating Expenditure |
| | | Indirect Labor |
| | Transportation Cost (factory only) | Module Transport |
| | | Police Escorts |
| | Local fees | State and Local Permitting |
| | | State and Local Taxes |

| | |
|---|---|
| **Soft Costs** | Developer Fee |
| | Legal |
| | Architectural |
| | Engineering |
| | Financing |
| | Permitting |

## Site-Built Cost

To create our site-built baseline cost scenario, our original intent was to use actual cost data available through our modular factory partner, KBS, in combination with RS Means and other costing databases. However, we were unable to get the detailed construction data required to complete this approach. Instead, the project team used new residential construction data from the US Census Bureau to find the average construction costs for site-built construction of multifamily homes.[21] These cost estimates include labor, material, architectural work, engineering work, overhead costs, interest and taxes paid during construction, and contractor's profits. These data do not distinguish between the efficiency level of the buildings or multifamily building type (i.e., high rise, low rise, townhomes etc.). Given that high-rise construction tends to have a lower cost per square foot the team considers the baseline cost used in this analysis to be a conservative estimate.

We used these data to estimate costs for the US and the Northeast region for years 2011 through 2020, calculating the average and range of construction costs over this time period. We did not find a significant difference in national and northeast construction costs and in Figure 17 present average costs for the northeast region. The cost of site-built construction has steadily increased between 2011 and 2020.

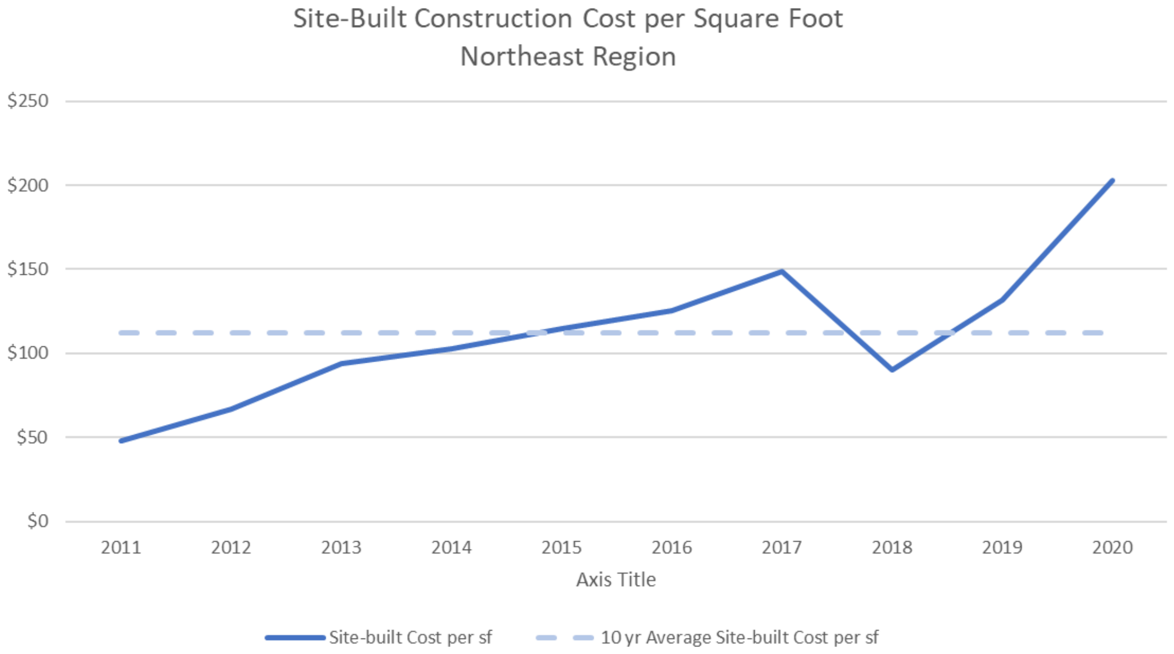


Figure 14. U.S. Census Cost of Multifamily Construction in the Northeast Region.

Looking only at the year 2020, the census data indicate that on average, site-built construction in the Northeast is $203 per square foot. We calculated a similar average cost using recent Vermont site-built projects: we obtained GMP Estimates (Guaranteed Maximum Price) for three Vermont multifamily building projects completed or under construction in 2020 to serve as a

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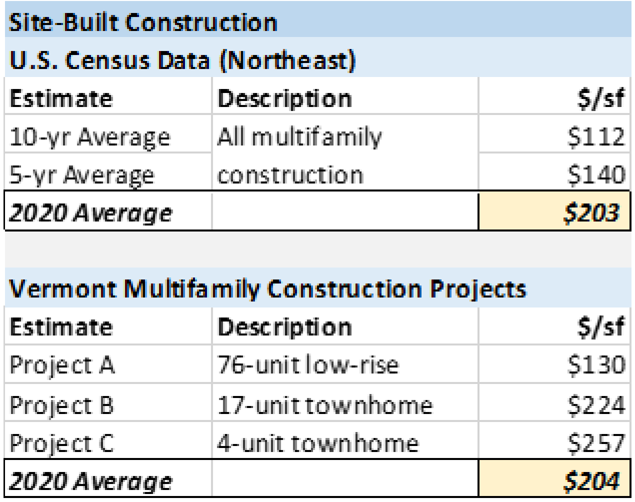
[21] See: **https://www.census.gov/construction/nrc/index.html.** We obtained construction costs for new MF and the number of new MF buildings completed by type of construction method (e.g., site-built, modular) by year and region.

comparison and validation of the Census data (Table 7). We opted to use 2020 Census data for the Northeast region to represent baseline costs.

Table 7. Site-built Multifamily Construction Cost Estimates.



**Site-Built Construction**

**U.S. Census Data (Northeast)**

| **Estimate** | **Description** | **$/sf** |
|---|---|---|
| 10-yr Average | All multifamily construction | $112 |
| 5-yr Average | | $140 |
| ***2020 Average*** | | ***$203*** |

**Vermont Multifamily Construction Projects**

| **Estimate** | **Description** | **$/sf** |
|---|---|---|
| Project A | 76-unit low-rise | $130 |
| Project B | 17-unit townhome | $224 |
| Project C | 4-unit townhome | $257 |
| ***2020 Average*** | | ***$204*** |

## 50% Better than Code Modular Cost

Our modular cost scenarios are based in part on cost data provided by KBS from a modular, multifamily building completed in 2011. Emerald Place is a 40,000 square foot, 24-unit modular box development in Lunenburg, MA. Although smaller, it is similar in layout to the prototype building used to develop the target EE packages. Emerald Place is not a zero energy building: to develop our target cost scenarios, we calculated an incremental cost for each energy efficiency (EE) package using pricing and labor estimates provided by KBS's cost estimation tool and other project partners. Some components of the Emerald Place construction costs were held constant, including common elements built onsite, lot preparation, transportation, overhead, and financing.

We estimate that as built, Emerald Place cost a total of $8.9 million. This estimate includes factory costs (labor and materials), as well as transportation of modules to the site and all site work (foundation, finishing work, permitting, etc.; see Table 8). We did not have actual pricing data for Emerald Place. The factory labor and materials were calculated by KBS using their detailed cost estimation tool and a database of current material, labor, overhead and transportation costs.  The physical characteristics of Emerald Place such as linear and square feet of materials were plugged into the tool to calculate factory costs.  Actual site costs from 2011 when Emerald Place was built were not available to the team and were estimated by KBS using professional judgement as 'about equal' to the factory costs. In practice actual site and soft costs are highly variable, driven by the local labor market and materials costs.

Table 8. Emerald Place Estimated Construction.

| **Cost Category** | |
|---|---|
| Factory - Materials, Labor, Overhead, Transportation | $4.8 million |
| Site - General Contractor, Materials, Labor, Overhead | $2.0 million |
| Soft Costs - Design, Permitting, Financing | $2.1 million |
| **Total** | $8.9 million |

There are many mechanical packages and ways to build envelope assemblies to the target performance levels. The detailed EE specifications were chosen with input from our modular building consultant familiar with KBS baseline processes and factory layout (Table 9). Component costs included in our cost model are real costs and labor estimates for available materials and technologies. EE package labor and material costs were compiled by the project team in collaboration with the KBS cost manager.

Table 9. EE Package Detailed Specifications.

| **Assembly/System** | *EE Target* | *Detailed Specification* |
|---|---|---|
| **Package 1: High Performance Mechanical Systems** | | |
| Heating | 13.5 HSPF<br>Cold Climate Heat Pump | HVAC Unit: Cold Climate Air Source Heat Pump<br>Haier Next Gen Arctic Mid-Static Ducted Heat Pump 12kBtu Indoor+Outdoor Unit w/ Gen Arctic Controller<br>Warren Technologies Duct Heater |
| Cooling | 22 SEER<br>Cold Climate Heat Pump | |
| Hot Water | 4.0 EF<br>Heat Pump Water Heater | Water H: Rheem Heat Pump Water Heater |
| Ventilation | 0.75 SRE<br>Heat Recovery Ventilator | Heat Recovery Ventilation: Broan HRV160<br>Honeywell CO2 On-Demand Control |
| Ducts | Inside conditioned space | |
| **Package 2: High Performance Thermal Envelope** | | |
| Frame Floor | R-40 | Floor Joists: 9-1/4" Open Joist Trusses (Spaced according to loads)<br>Insulate with Dense Pack Cellulose with Insuleweb Netting at bottom |
| Ceiling/Roof | R-60 | R-60 Dense Pack Cellulose Ceiling Insulation (Upper Floor) |
| Above Grade Walls | R-30 | Wall Framing: 8" Thick - Double 2" x 4" Studs (Double Top Plate and Single Bottom Plate)<br>R-30 Dense Pack Cellulose Wall Insulation (8" Wall) |
| Windows | U-0.22 | Triple pane, Low-e, argon, insulated frame |

| | | |
|---|---|---|
| Air tightness | 1 ACH50 | Apply Blueskin, taping all plate lines, vapor retarder on inside |
| **Lighting & Appliances** | | |
| Lighting | 100% LED | 100% LED |
| Appliances | ENERGY STAR | ENERGY STAR[79] |

As noted above, the modular scenario is a standard factory layout and process, rather than a factory optimized for construction of high-performance units. Although we identified some general areas for improvement in the KBS factory, as well as other cost-optimization strategies to reduce construction costs, we are modeling the cost to build the target packages in the factory under current conditions, using the existing layout.

## Cost Model Results

We estimate that the total cost of construction for a modular, multifamily building that achieves 50% better energy performance is 11-14% higher than a site-built 2018 IECC-compliant baseline (Table 10). EE Package 1 (high-performance mechanical system) was the most cost-effective, achieving the project’s energy performance goals at an overall cost of 11% more than baseline. EE Package 2 (high-performance envelope) was 14% higher than the site-built baseline, and EE Package 3 (combination of Packages 1 and 2 to achieve a zero-energy standard) was 16% higher. These incremental costs are in-line with national estimates for this level of efficiency. As a percentage of overall construction costs, the impact of the EE packages was minimal, representing on 2-6% of total project costs. As noted above, construction costs drawn from U.S. Census and actual building cost data suggest that modular costs were approximately 9% higher than site-built construction costs for the base case scenario.

Table 10. Total Cost of Construction for Site-built Baseline and Modular Target Scenarios.

| Construction Scenario | Total Cost of Construction | Increase over baseline |
|---|---|---|
| Site-built, 2018 Code | $8,244,615 | - |
| EE Package 1 | $9,153,903 | 11% |
| EE Package 2 | $9,382,274 | 14% |
| EE Package 3 | $9,541,312 | 16% |

Using the Emerald Place cost data as a basis allowed us to isolate the incremental cost of the EE packages including both material and labor. Considering only the EE improvements and not other construction costs, EE Package 1 was 25% higher, Package 2 was 33% higher, and Package 3 was 30% higher relative to an equivalent baseline assembly built with modular construction. Inclusive of all construction costs, a more common way of reporting incremental costs over baseline, the high-performance envelope packages were 2 - 6% higher than base case modular costs (Table 11).

Table 11. Incremental Costs of EE Packages Relative to a Code-compliant Modular Building.

| | **Emerald Place (base code)** | **EE Package 1** | **EE Package 2** | **EE Package 3** |
|---|---|---|---|---|
| | | | | |
| ***Envelope*** | ***$589,622*** | ***$589,622*** | ***$783,327*** | ***$783,327*** |
| Material | $277,122 | $277,122 | $388,815 | $388,815 |
| Labor | $129,717 | $129,717 | $163,759 | $163,759 |
| Other | $182,783 | $182,783 | $230,752 | $230,752 |
| | | | | |
| ***Mechanicals*** | ***$314,609*** | ***$394,128*** | ***$314,609*** | ***$394,128*** |
| Material | $151,235 | $140,748 | $151,235 | $140,748 |
| Labor | $68,844 | $253,380 | $68,844 | $253,380 |
| Other | $94,530 | $0 | $94,530 | $0 |

Our cost model also assessed if reductions in material waste and improvement in quality could eliminate the incremental costs of the EE packages. As show in Table 12, when material waste and labor quality costs are reduced by 22%, EE Package 1 can be constructed at similar costs as the baseline modular scenario. For Packages 2 and 3, cost reductions in these two categories would need to increase by 53% and 74%, respectively. As a factory gains experience with implementing new processes and building with new materials, we expect the required cost reductions would decrease over time. At this point in the project, we are assessing how the existing KBS factory process can be improved and optimized for ZEM multifamily construction and integration of EE components.

Table 12. EE Package Material Waste and Cost of Quality Reductions Required to Eliminate Incremental Cost Relative to Modular, Base Code Building.

| | **Emerald Place (base code)** | **EE package 1** | **EE package 2** | **EE package 3** |
|---|---|---|---|---|
| Cost increase over modular base code | - | $159,038 | $387,409 | $546,447 |
| Increase over modular base code | - | 2% | 4% | 6% |
| **Level of improvement required to eliminate cost increase over modular base code** | | | | |
| Material Waste Reduction | - | 22% | 53% | 74% |
| Cost-of-Quality Reduction | - | 22% | 53% | 74% |
| **Value of Improvements** | | | | |
| Material Waste Reduction | - | $110,543 | $272,482 | $386,448 |

| | Emerald Place (base code) | EE package 1 | EE package 2 | EE package 3 |
|---|---|---|---|---|
| Cost of Quality Reduction | - | $46,060 | $113,534 | $161,020 |
| Total Cost of Construction After Improvements | **$8,994,865** | **$8,997,300** | **$8,996,258** | **$8,993,844** |

Our top-down cost modeling results show that under our current scenario, modular construction cannot yet achieve 50% better than site-built code at no extra cost solely through savings from material waste and labor quality. This case study highlights the challenges associated with using construction costs as a metric: actual costs are difficult to obtain and normalize across projects.

In the following case study, we explore the savings available through process improvements (labor, quality, and waste savings) that can be achieved within the existing factory layout. We draw on results from a KBS time study and DES conducted by the project team to identify opportunities to bring modular construction costs in line with site-built costs.

# Case Study: Zero Energy Factory Building

A modular construction system devoted to ultra-efficient, high-performance construction begins with the factory itself. We used energy modeling to explore if all-electric, high-performance factories with ventilation could be cost-effective to own and operate relative to more standard modular factories. Our goal is to create a factory design that is a comfortable and safe environment for workers and minimizes energy use. Our modeling compares a baseline, traditional modular factory to an efficient, all-electric factory.

**GOAL**: design an all-electric, high-performance modular factory that is cost-effective to own and operate.

**METHODS**: We modeled over 1,000 scenarios in the Open Studio Parametric Analysis Tool (PAT) and analyzed 360 factory models.

**RESULTS**: Our modeling showed that an all-electric modular factory can be much more cost-effective to operate than a traditional factory powered by propane, electricity, and gas unit heaters. The HVAC target scenarios reduced annual energy costs by more than 60%. The HVAC system type has less impact on building energy use when the building is highly airtight. However, even with the highest building airtightness, VRF and DOAS with VRF ultimately, still have lower energy costs than gas unit heaters and PSZ-AC.

## Methods

We modeled over 1,000 scenarios in the OS Parametric Analysis Tool (PAT), capturing the combination variables listed in Table 13 below. 360 models remained for analysis after excluding the unintended or unrealistic scenarios. We used 2018 energy costs (at industrial building rates), available through NYSERDA, for the modeling.[22, 23] Both the baseline and target factory are assumed to be 207,000 ft$^2$ and in Albany, NY (Climate zone 6A).

**Baseline Factory**: The baseline factory is assumed to be powered by propane and electricity, and to have low airtightness, propane unit heaters without cooling and ventilation, and constant

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[22] "Monthly Average Retail Price of Electricity - Industrial," *NYSERDA*. **https://www.nyserda.ny.gov/Researchers-and-Policymakers/Energy-Prices/Electricity/Monthly-Avg-Electricity-Industrial** (accessed Feb. 07, 2023).

[23] "Annual Energy Prices," *NYSERDA*. **https://www.nyserda.ny.gov/Researchers-and-Policymakers/Energy-Prices/Annual-Prices** (accessed Feb. 07, 2023).

temperature setpoint at 50 °F for heating. These factory characteristics are based on the KBS factory and are consistent with factories found in the northeast.

**Target Factory**: The target factory is assumed to have above-code roof and wall insulation and either a Variable Refrigerant Flow (VRF) HVAC system or a Dedicated Outdoor Air System (DOAS) with VRF system. Factory hours of operation are similar between the target and baseline factories; temperature setpoints differ (Table 13). For the target factory, the zero energy target was calculated as (Energy production – Energy consumption ≥ 0). We estimated energy production from rooftop solar PV to be 1.7 million kWh based on the surface area of the roof (minus the perimeter area).

Table 13. Factory Energy Modeling Variables and Scenarios.

| | Baseline | Target Scenarios |
|---|---|---|
| **ENVELOPE** | | |
| **Wall R-value** | R5 | R5; R30 |
| **Roof R-value** | R5 | R5; R60 |
| **ACH** | 1.26 | 0.06; 0.31; 0.63; 1.26 |
| **LOADS** | | |
| **Lighting** | 0.34 kWh/ft$^2$ | 0.34 kWh/ft$^2$ |
| **Equipment** | 1.04 kWh/ft$^2$ | 1.04 kWh/ft$^2$ |
| **CONTROL** | | |
| **Heating Setpoint** | 50°F, no setback | 50°F/95°F, no setback; 65°F /80°F no setback; 65°F /80°F with 15°F setback |
| **Cooling Setpoint** | No cooling | |
| **Hours of Operation** | 7am-3pm; 7am-11pm | 7am-3pm; 7am-11pm |
| **HVAC** | | |
| **Heating System** | Wood/propane furnace | PSZ-AC with gas coil; Gas unit heaters; VRF; DOAS with VRF |
| **Cooling System** | No cooling | |
| **Ventilation** | No Ventilation | |

# Results

Our modeling showed that an all-electric modular factory can have lower energy costs relative to a traditional factory powered by propane, and electricity. On average in the 90 scenarios generated for each HVAC system type, the target scenarios, using VRF or DOAS with VRF systems, used less than half energy than the baseline scenarios, which depended on propane gas unit heaters or PSZ-AC with gas coil (Figure 18). **The HVAC target scenarios reduced annual energy costs by more than 60%.** The HVAC system type is less impactful on building energy use when the building is highly airtight. However, results show that even with the highest building airtightness, VRF and DOAS with VRF ultimately still have lower energy costs relative to gas unit heaters and PSZ-AC.

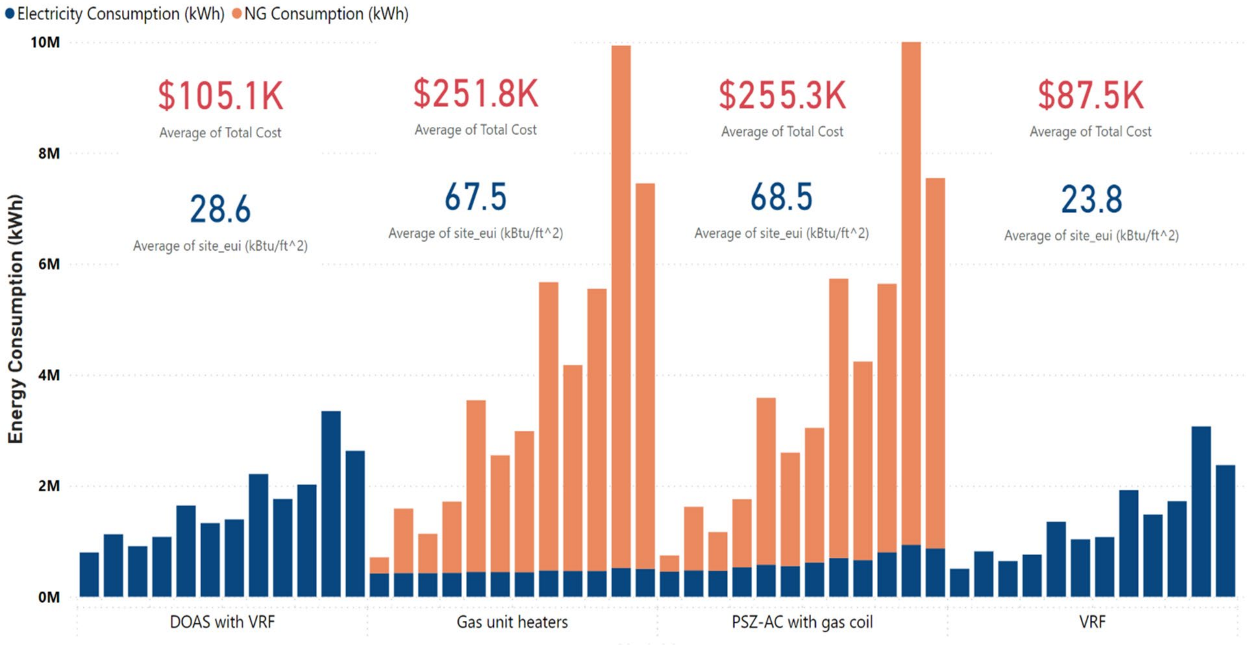

Figure 15. Energy Consumption and Utility Costs for HVAC Scenarios.

Overall, variation in cost within the target scenarios (those using VRF and DOAS with VRF) were much smaller than with the baseline scenarios, which depended on propane gas unit heaters. Within the target scenarios, utility costs ranged from $28,000 to $188,000, depending on building airtightness, HVAC controls, and hours of operations. In contrast, we estimate that utility costs for the baseline factory using propane gas unit heaters would vary from $41,000 to $611,000.

## Meeting the Zero Energy Target

The target scenario (a factory building with VRF or DOAS with VRF) can meet the zero energy target when the energy production from rooftop solar PV is 1.7 million kWh and the building has a higher airtightness (blue bars in Figure 19). At lower airtightness (either or both less efficient envelope or/and more door openings), temperature setpoints, HVAC controls, hours of operation (i.e., occupant behavior) can impact the feasibility of reaching zero energy. Because in the building with DOAS with VRF the HVAC system provides ventilation for the building, it is assumed that the number of door-openings for air refreshing in the manufacturing area would be minimized compared to the VRF without ventilation. Hence, it is more realistic to compare DOAS with VRF at lower infiltration multiplier value with the VRF system type at higher infiltration multiplier value as shown in the highlighted bars in Figure 2. The average utility cost is lower for the DOAS with VRF option in comparison to VRF because of reduced heating demand due to door openings. This is achieved despite the added energy use for ventilation and heat recovery in the DOAS system.

Both the VRF and DOAS with VRF HVAC systems were able to achieve the zero energy target, in combination with an energy efficient envelope, only with a less desired temperature setpoint (heating setpoint 50° F / cooling setpoint 95° F) or desired temperature with a setback (heating setpoint 65° F / cooling setpoint 80° F with a setback of 15° F), regardless of hour of operations.

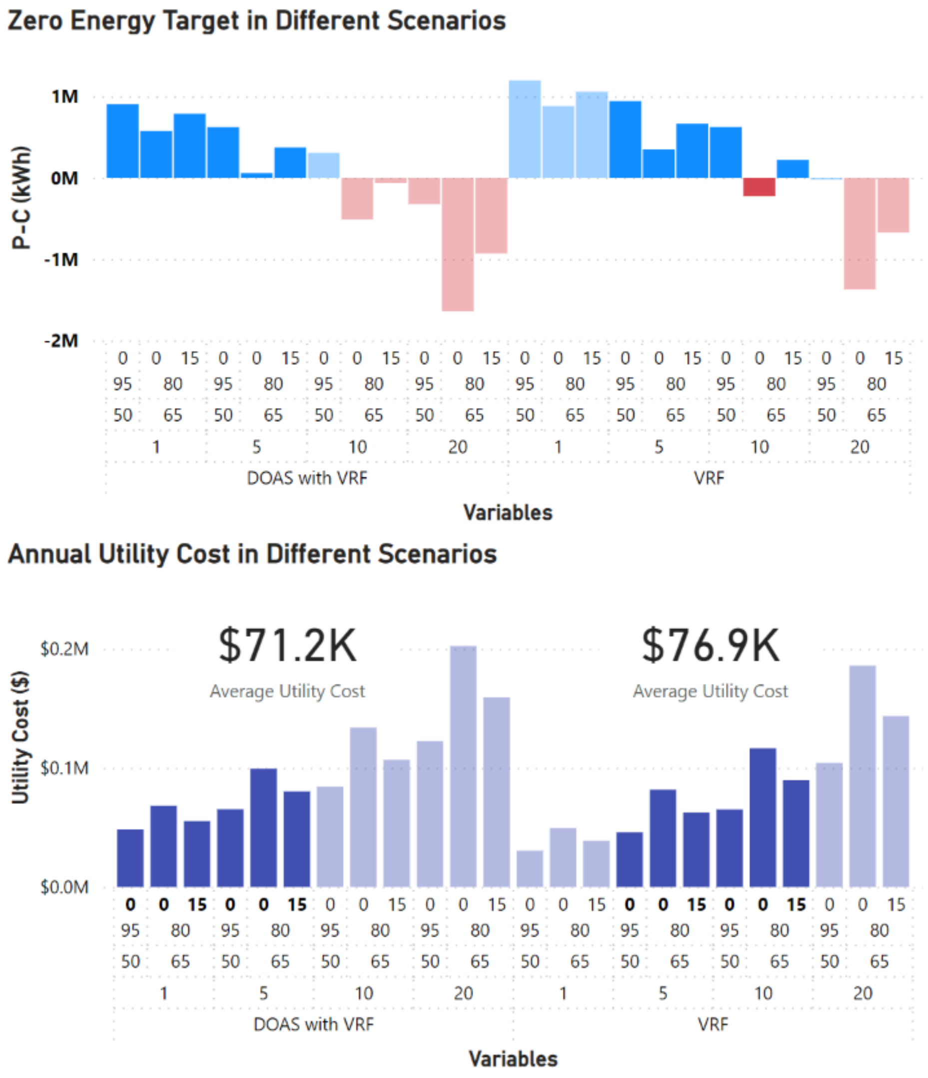

Figure 16. Zero Energy Target and Utility Cost Comparison in DOAS with VRF and VRF scenarios.

## Conclusion

In our modeling the target scenario HVAC systems (VRF and DOAS VRF) were more efficient and cost-effective to operate than the baseline scenario, regardless of building airtightness, hours of operations, and temperature setpoints and controls. Providing cooling and ventilation for this type of building is financially viable with an all-electric building. This target building, which includes above code wall and roof insulation and programmable thermostat with a setback for temperature setpoints not only can achieve net-zero energy target, but also provides thermal comfort and a healthier environment for building occupants. Building with above-code insulation and DOAS VRF or VFR with similar temperature setpoints, controls, and hours of operation to the baseline could reduce annual utility cost by 80% in comparison to the baseline (~$278K a year).

We also found that setback for temperature setpoints can have a considerable impact on energy savings.

# Case Study: Integrating Energy Efficiency Strategies into Existing Factory Processes

## Background

In order to identify cost effective methods into an existing factory, the team evaluated the current production process of a KBS, the project's modular factory partner. For almost 20 years, this facility has been designing and manufacturing modular structures with a commitment to residential housing, net zero design, commercial, and mixed-use buildings.

KBS's core business is residential construction, and they build both single-family and multifamily modular homes (Figure 20). Their designs for residential modular homes range from code-level construction to Certified Passive House and simple one module designs to more complicated multi-module luxury homes. They are also a leading builder of multifamily and commercial modular facilities throughout the New England area. Designs for commercial construction include apartments, student and senior housing, and net zero hotels. KBS's factory is a 70,000 sq ft facility, using a U-shaped production line with 19 main workstations and 6 feeder stations.

**GOAL**: Eliminate the incremental cost of Energy Efficiency packages through improvements in waste and quality at an existing modular factory.

**METHODS**: We conducted a video time study in the KBS factory to capture detailed data on existing processes. We used these data to create discrete event simulation, modeling baseline factory processes and scenarios incorporating the energy efficiency packages that simultaneously reduce waste and improve quality.

**RESULTS**: The energy efficiency strategies can be added to the main production line without impacting the weekly production rate of 8 modules completed per work week, *if* key work stations undergo line balancing strategies.

Figure 17. Participating Modular Factory Residential and Multifamily Home Projects.

## Incorporating Energy Efficiency Packages into the Existing Line

Through improvements in waste and quality at KBS, the project team aims to eliminate the incremental cost of the Energy Efficiency (EE) packages. Thus, achieving 50% better energy performance than code at no extra cost. The team conducted a time study to capture detailed data on the existing processes, created a discrete event simulation (DES) to model the baseline factory process and developed  scenarios to reduce waste and improve quality incorporating the energy efficiency packages developed in our previous modeling exercise.

Table 14. Construction Scenarios.

| Construction Scenario |
|---|
| Site-built, 2018 Code |
| EE Package 1- high-performance mechanical system |
| EE Package 2- high-performance envelope |
| EE Package 3- combination of Packages 1 and 2 to achieve a zero-energy standard |

Outputs from the simulation were used to develop recommendations for existing and new modular factories interested in producing ZEM multifamily homes.

## Time Study and Factory Data Collection

The team visited the KBS factory and developed a nuanced understanding of their existing processes. We identified changes in the production line that need to occur to build a high-performance multifamily building that meets the project goal of 50% better energy performance than the 2018 IECC target. Over the summer and fall of 2021, the team conducted a time study with seven cameras installed in the factory to record production operations. This time study allowed the project team to gain a better understanding of current production capabilities and identify areas to integrate the EE package components into the production line. The team reviewed the videos to quantify and document the work scope, performance (e.g., labor time, quality outcome, material waste), and input/output of all workstations, with particular attention to those stations related to the installation of EE packages.

Videos also provided insight on the workflow and where tasks were being started and completed, and how this compares to the workstation assignments in the quality manual. In addition, KBS provided a full set of drawings and the traveler documents of the units built during the study period.

## Discrete Event Simulation

The project team followed an integrated methodology (Figure 21) to create a simulation of the current production process incorporating EE packages and developed an improved process. The baseline process model serves as a platform to study how and where new activities can be integrated. These new activities are referred to as 'what if scenarios' since they are not part of the current production process.

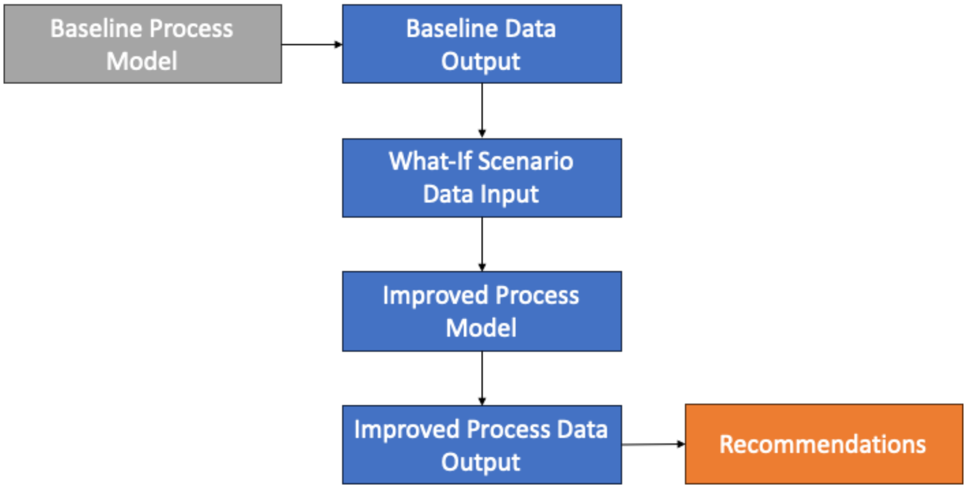

Figure 18. Integrated Process Model Methodology.

## Current Factory Construction Process - Baseline

As noted above, the KBS factory is a 70,000 sq ft facility, using a U-shaped production line with 19 main workstations. Workstations 16-19 are located outside of the facility due to limited space and are mainly used for storing finished modules. There are 6 feeder stations (e.g., CNC saw, wall framing, etc.) that support the main production line. The layout of the facility is shown in Figure 22. Details of the production line and performance are included in Appendix A. The production capacity assumes a single production shift at 46.4 hours per working week, 8 hours per shift with an average of 1.3 hours of overtime. Production is supported by 90 workers each shift. The current production level is 8 modules per week, driven by 1.6 modules moves per day. This means there is a line move every 5.8 hours.

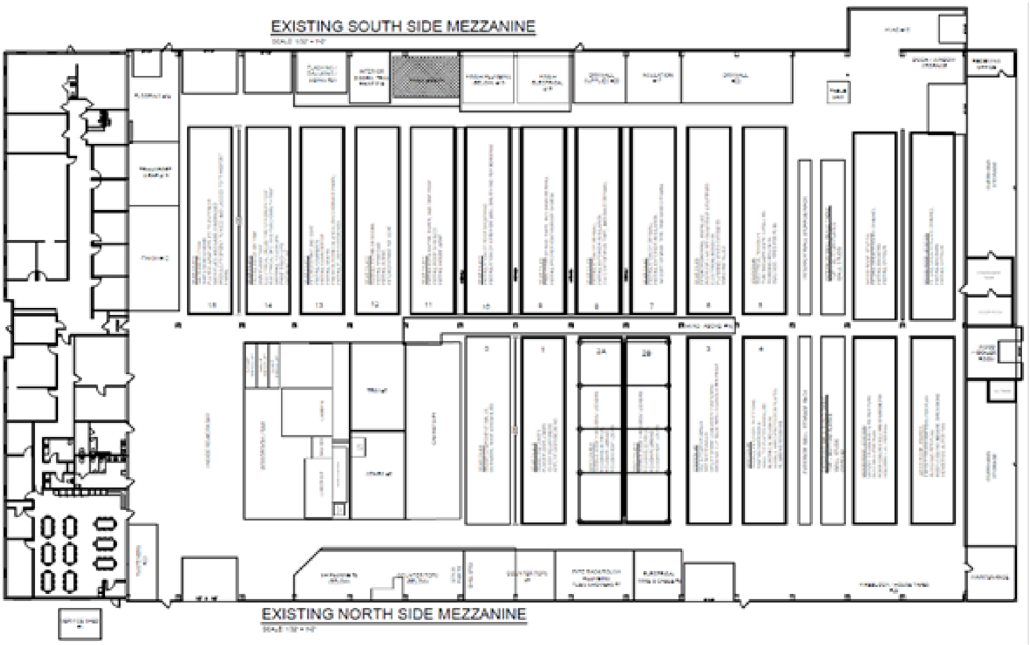

Figure 19. Participating Modular Factory Current Layout.

The facility has material handling systems which help to move material and modules on the production line. Table 15 below lists each handling system, with descriptions of each.

Table 15. Material Handling Systems.

| Material handling system | Quantity | Comments |
|---|---|---|
| Overhead crane assembly | 2 | 2-tons capacity on the north side of factory |
| Overhead crane assembly | 1 | 3-tons capacity on the north side of factory |
| Overhead crane assembly | 3 | 2-tons capacity on the south side of factory |
| Overhead crane assembly | 1 | 3-tons capacity on the south side of factory |
| Overhead crane assembly | 2 | 2-tons capacity in the welding shop |
| Fork trucks | 2 | 9,000 lb capacity |
| Fork trucks | 4 | 5,000 lb capacity |
| Pallet jacks | 2 | 4,000 lb capacity |
| House jacks | 6 | 16,000 lb capacity |
| Transport carts | 6 | |
| Power pushers | 2 | Battery operated to move modules on the production line |

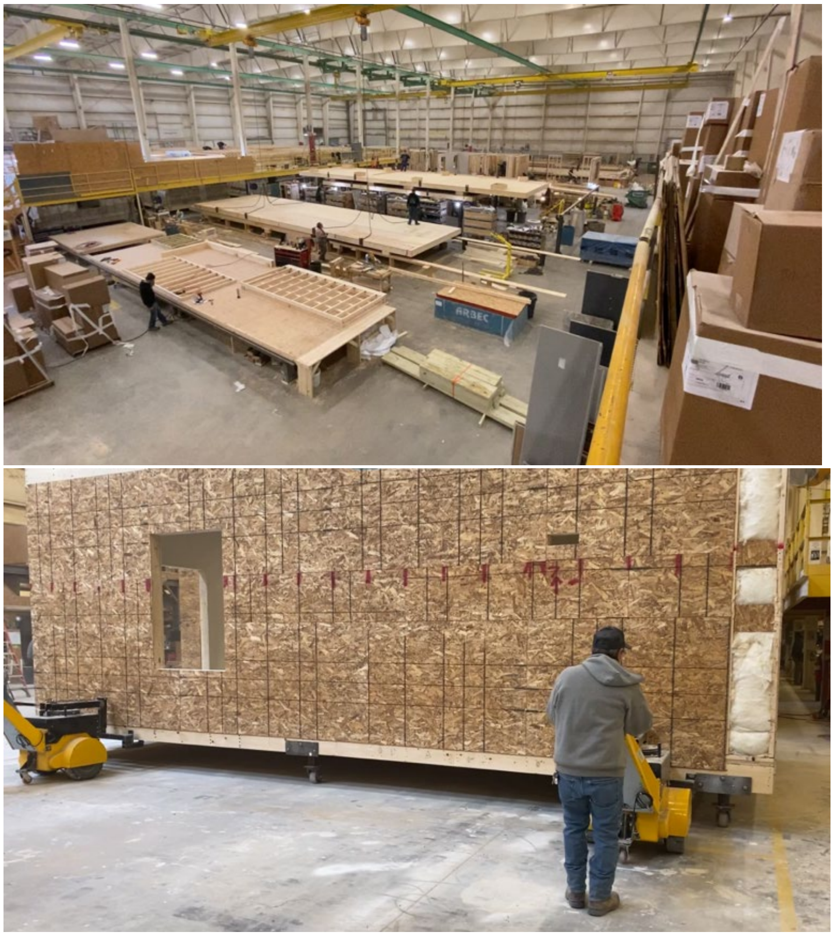

Figure 20. Material Handling System- Cranes and Power Pushers.

The baseline process simulation uses information and data from the existing plan layout of KBS, current activities, and existing active equipment on the factory floor. The time study described above helped us understand the existing conditions and identify early opportunities to improve weekly productivity, reduce downtime at or in-between stations, and add new activities without undermining the current weekly productivity.

To document the current conditions and create the baseline process model, the project team followed a multi-variable monitoring and data collection strategy (See Appendix E). Activity duration data were gathered using a combination of expert interviews, manually documented time stamps from 'travelers', and data-collection methods using video data obtained from the KBS factory.

The data collection strategy allowed the project team to measure and evaluate productivity improvements to validate the following:

- If a proposed approaches for specific energy efficiency strategies is more efficient compared to the baseline or traditional approach and;

- If a proposed approach for specific energy efficiency strategies incurs less cost and takes less time to complete the final built product (start to finish to delivery) than an alternative approach or the baseline traditional approach.

Through continuous improvement and experiential learning effects, the proposed approach for specific energy efficiency strategies can further reduce the time to complete (start to finish to delivery of the EE packages), cost, and labor-hours compared to the baseline traditional approach (average productivity in the industry today).

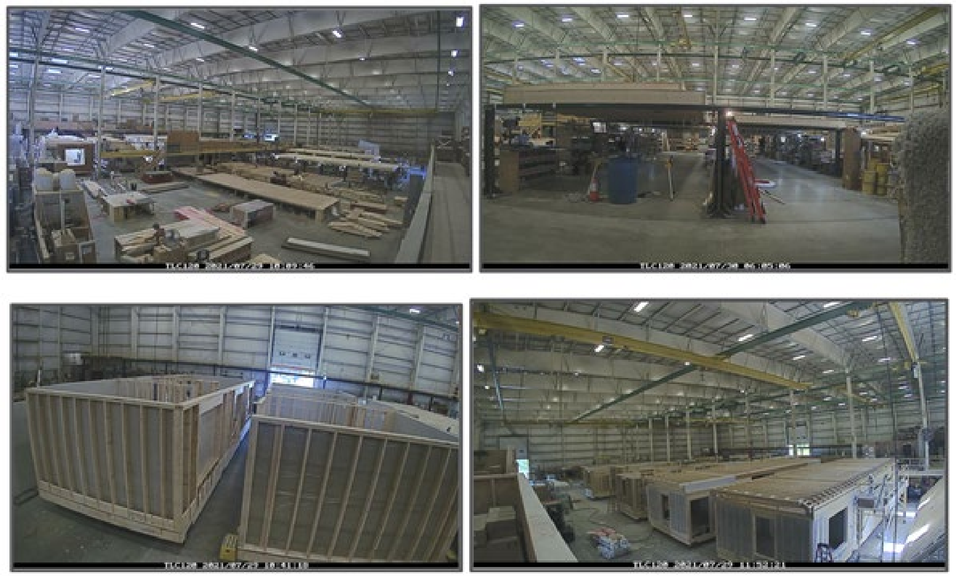

Figure 21. Video Data from the KBS Factory.

Key assumptions helped fill data gaps in the factory data collection package to inform the baseline process simulation model. The following key assumptions informed the baseline process model:

- Completion of one module takes an average of 87 hours (average 5.8 hours at every station for one module).
- Work at stations 5 to 12 occurs at 50%-75% of its capacity. This means, during completion of one module, there is a total downtime of 27.55 hours.
- An average of 50% of total downtime per working week is allocated to workers' break time and equipment's idle time.
- At least 2 interior walls need to be completed every 2 hours with 2 workers.*
- Storage for at least 10 interior walls.*
- At least 2 exterior walls need to be completed every 2 hours with 2 workers.*
- Storage for at least 10 exterior walls.*

- At least 2 roofs need to be completed every 2 hours with 2 workers.*
- Storage for at least 10 roofs.*

(**Simulation method* - checked when and where the model breaks/shows error)

The project team created a baseline process simulation model in AnyLogic$^{TM}$ software. The baseline process simulation model acts as a digital twin of the real-world physical factory since it accurately reflects the 2D floor plan layout of the KBS factory (Figure 25), the factory construction schedule, the workers and resources allocation in each station, the weekly productivity, and the work time in each station.

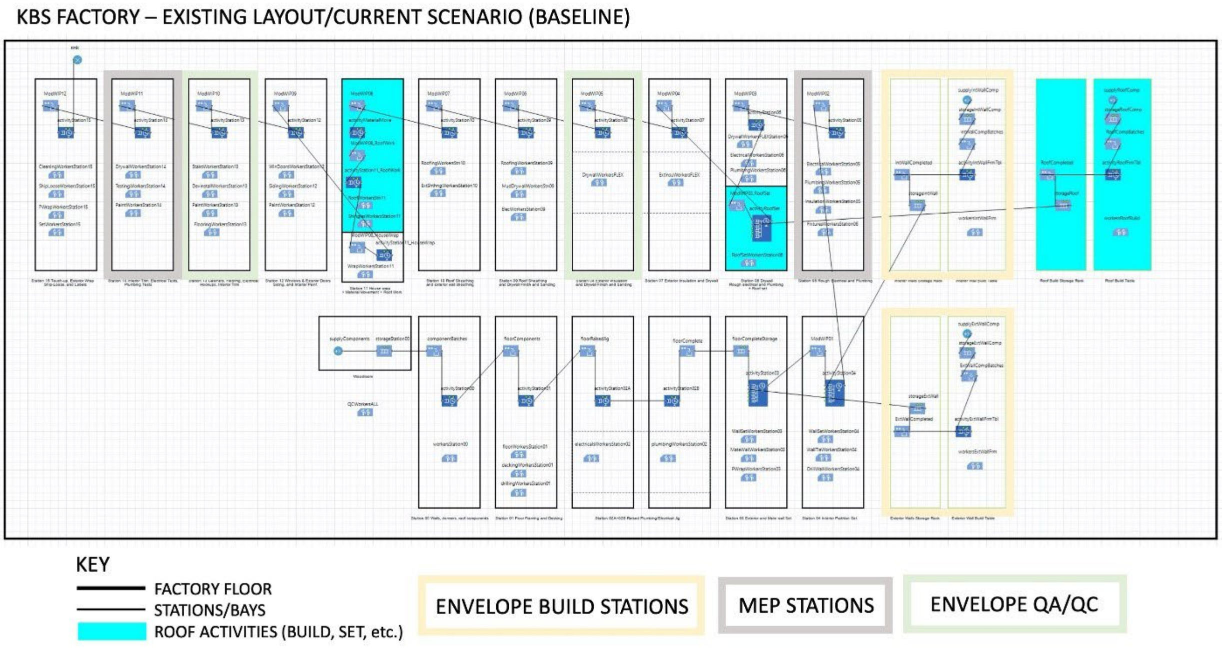

Figure 22. Baseline Process Simulation.

## DES Modeling to Analyze Energy Efficiency (What if Scenarios)

The baseline data output (see Appendix C) helped the project team readily conduct a process analysis of the production line under the influence of newly introduced what if scenarios related to EE specs integration. Examples of such changes include varying the number of workers assigned to a station, varying the number of surge spaces for different stations, and alternating the placement of various tool stations. Because of the tight integration between (1) the factory layout, (2) the factory resources, and (3) the construction process, the result of any changes on either will be considered in the total construction efficiency (e.g. production rate) achieved by the KBS factory.

As part of this project, the project team has leveraged this baseline process model to understand how any change in any one of these aspects affects the availability, the surplus, and the position of the others in the production line, acting as feedback to inform continuous improvement . The project team found the following key outcomes from the baseline data output (see Appendix A):

- Total time to complete each module is 95.95 hours on the main production line, not including batch production from feeder stations that are active simultaneously. This estimate is based on the baseline model assumptions described above, resources, schedules and breaks, and downtime.
- Those 95.95 hours include 6.6 hours of roof related activities and 89.4 hours of all other activities including observed downtime (see Figure 28).
- Stations 5 to 12 (downstream activities) are being utilized at 50%-75% of their maximum capacity. The model has quantified the total downtime per module in stations 5-12 to be 27.6 hours (see Figure 26).
- Running the baseline simulation model for ~100 hours shows the weekly production as 8 modules completed per work week.
- 7.5 hours per module is spent on activities related to MEP systems (e.g., a ducted cold climate heat pump with an integrated ERV and HPWH), including electrical and plumbing roughing and testing
- 3 hours per module is spent on activities related to envelope QA/QC
- We have highlighted all the baseline data outputs and assumptions related to roof activities (build, set, etc.) in the table under Appendix A; Includes the feeder station with roof build activities, Station 6 and 7 for roof set, and Station 11 for roofing work.
- At Station 6, 0.50 hours are spent on roof set and 5.67 hours are spent on other activities.
- Observation shows that roof set frequently happens at Station 7.
- At Station 11, 3.67 hours are spent on material movement (50% of the total time), 2.4 hours are spent on roofing work, and 1.25 hours are spent on house wrap activities.
- Model assumptions were made for supply and storage of raw materials for walls and roofs.

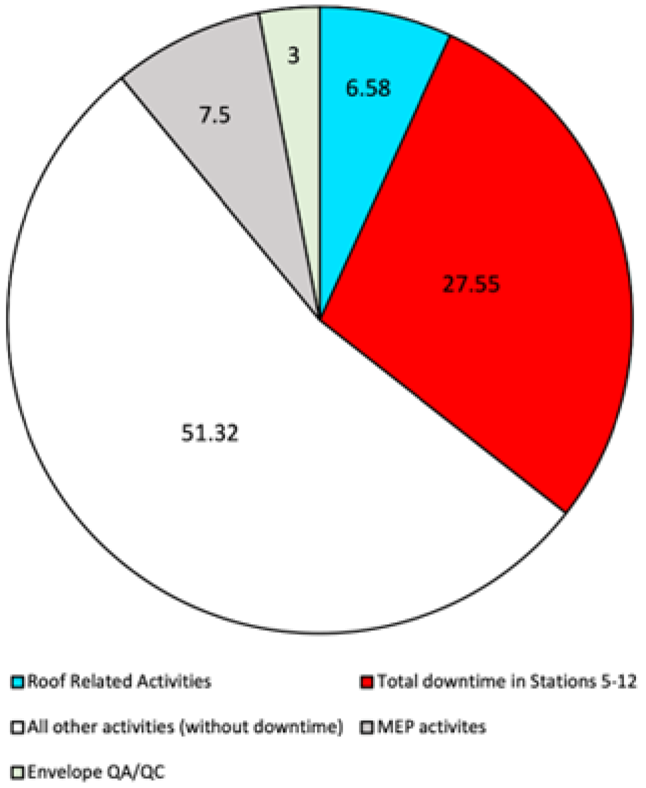

Figure 23. Baseline Total time taken (in hours) for Activities on the Main Production Line to Complete One Module at the KBS Factory.

The project team identified opportunities to increase the weekly production to 9-10 modules per work week if the following changes are made (Simulation method: values were doubled and how this change affects the main production line was checked):

- Build 4 exterior walls every 2 hours with 4 workers as well as double their storage capacity.
- Build 4 interior walls every 2 hours with 4 workers as well as double their storage capacity.
- Build 4 roofs every 2 hours with 4 workers as well as double their storage capacity.

The Project Team leveraged the baseline process simulated and interviewed a subject matter expert to determine the incremental time, if any, due to the required work for the EE installation. The team followed up with a line balancing analysis to accommodate the required tasks related to the installation of EE packages and meet the ideal weekly production rate of 10-15 modules completed per work week.

## Improved Factory Layout for Construction of High-Performance Buildings

Based on the time study and DES analysis, the project team developed an improved KBS factory layout for construction of high-performance buildings by creating a scenario model. The improved process leveraged the baseline process model (Figure 27). The following major changes were introduced:

- High-performance envelope build at feeder stations:
- Additional activities (see Appendix A) do not affect the main production line since these activities are part of feeder stations
- The envelope builds feeder stations have a high throughput which leads to high storage capacity of envelope. The feeder stations would still remain balanced after added steps from high-performance envelope build are introduced.
- Re-organization of roof activities:
- Moving post-set roof activities upstream and on the floor closer to roof build station
- Roof set activity shifted (along with solar PV) to Station 7
- Introduction of all 13 activities related to solar + storage installation:
- Feeder station with roof build: Solar roofing activities performed on the factory floor. Moving the solar roofing activities to the floor closer to the roof build as an extension of the feeder station reduces the total time for related activities by 50%. This also serves as an effective line balancing strategy.
- Station 5: Solar ready activities performed along with electrical roughing
- Pre-roof set activities: Mounting and solar decking activities on the floor, immediately after solar roofing
- Post-roof set activities: Solar PV install activities after the roof is set
- Home battery installation activities: Small, decentralized home battery installed after the interior paint activities

- Combination of downstream stations leading to line balancing and removal of one station:

- House wrap activities from baseline process model’s station 11 gets re-organized into proposed scenario’s station 10 (as shown in Figure 27) to form a combined station and leads to line balancing

- Removal of baseline process model’s Station 10 (indicated as grey rectangle in Figure 27 in proposed scenario process model) leads to efficient spatial organization of the factory floor and room for the new activities on the factory floor

- MEP installation activities in the utility room:

- At Station 10, the unitized MEP systems are installed along with advanced controls

- Installing MEP systems takes 7 hours per module (including electrical and plumbing roughing) followed by 30 minutes of testing

- Dedicated in-factory airtightness improvement activities: [24]

- Every module takes a total of 1 hour for envelope airtightness improvement (including 20 minutes for ionized sealing action if needed)

- The baseline cycle time for envelope QA/QC was reduced from aggregated 3 hours to 1 hour due to the repeatable process. This serves as a line balancing strategy.

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[24] Use of AeroBarrier equipment to improve airtightness was modeled at workstation 8 but the project team does not believe it's feasible for modular new construction.

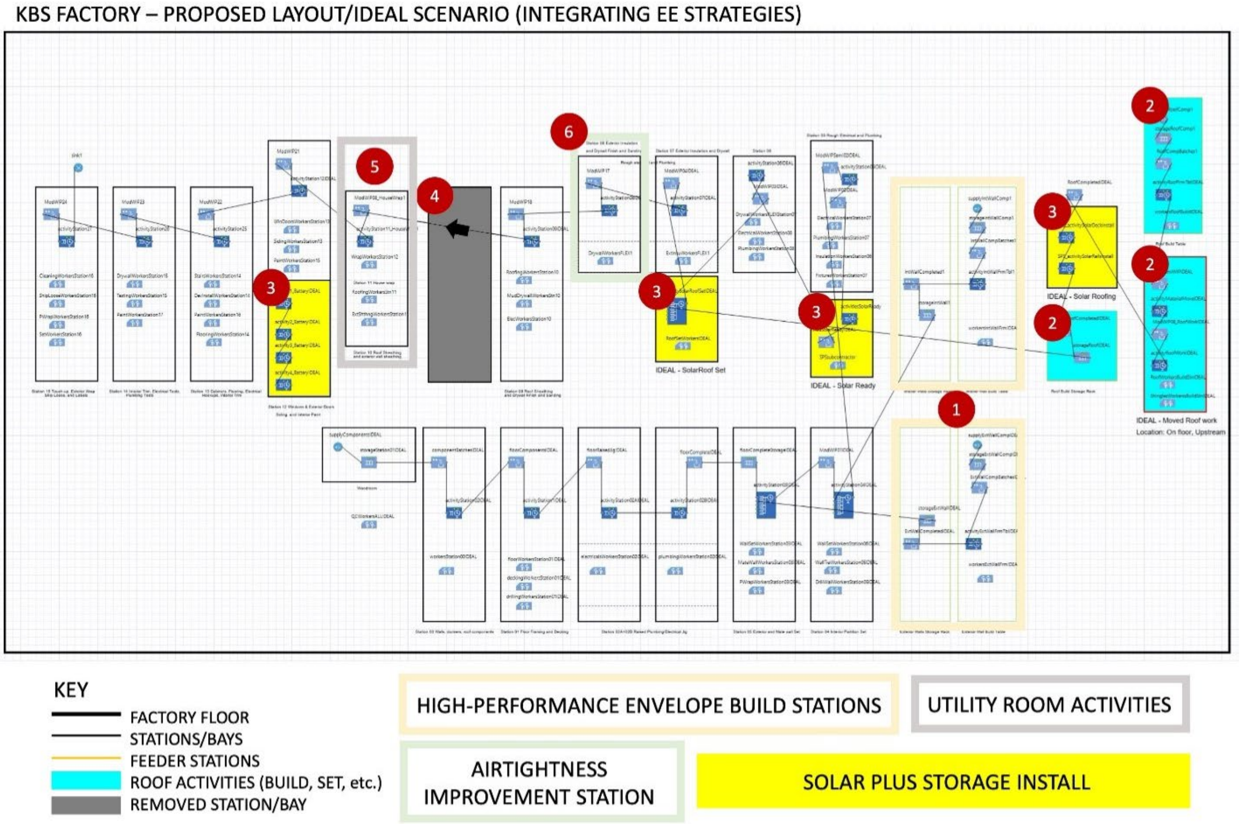

Figure 24. Proposed KBS Factory Layout Based on Ideal Process Simulation Model.

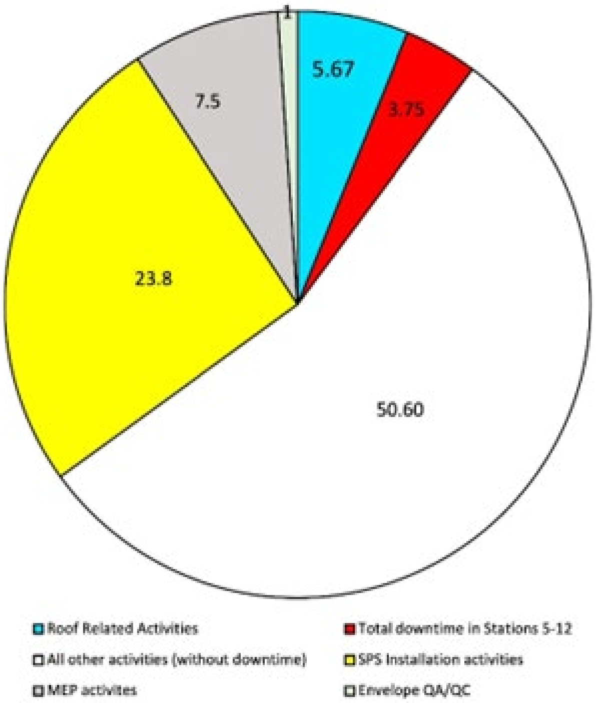

Figure 25. Total Time (in Hours) for Activities on the Main Production Line to Complete One Module Under Proposed Scenario.

The project team leveraged the proposed scenario data output (see Appendix B) to inform recommendations for optimized improvements to the current scenario. The following are key outcomes from the proposed scenario data output:

- Executing or running the baseline simulation model for ~100 hours shows the weekly production as 8 modules completed per work week.
- Total time to complete each module (considering model assumptions, resources, schedules and breaks, downtime) is 92.3 hours (only on the main production line, not including batch production from feeder stations that are active simultaneously). Total times breaks down to include:
- 5.7 hours of roof related activities
- 7.5 hours from MEP installation activities in the utility room (including electrical and plumbing roughing),
- 23.8 hours from solar plus storage installation (excludes pre-set roofing activities that are part of the feeder station),
- 1 hour for envelope QA/QC (including optional AeroBarrier action), and 50.6 hours of all other activities including observed downtime (as shown in Figure 28),

- The total downtime per module in stations 5-12 of 27.5 hours served as the primary source of opportunity to add new activities.

- Stations 7, 8, 9, 12, and 13 have been subjected to line balancing leading to 100% utilization (5.8 hours per station per module).

- Station 8 and 9 have similar activities and therefore have been combined. Workers and resources move between these two stations.

- At Station 10, MEP systems are installed into the utility room.

- At Station 8, the dedicated envelope QA/QC station reduced the total cycle time

- We have highlighted all the proposed scenario data outputs and assumptions related to roof activities (build, set, etc.) and new activities related to integration of energy efficiency strategies in the table under Appendix B.

- At Station 7, 0.50 hours is spent on the solar roof set, like a typical roof set activity. Since all roofing activities have moved to the floor close to roof build station, only exterior wall sheathing, and house wrap activity from baseline station 11 can be combined to Station 10.

- Station 10 now includes post-set roofing activities. These activities are performed by the sub-contractor in parallel to exterior wall sheathing, and house wrap activity. These activities will not get added to the total time in Station 10 since the activities are performed in parallel by a non-conflicting crew.

## Case Study Results

The project team performed a comparative analysis of baseline model and proposed scenario model data outputs (i.e., performance). Appendix A highlights the comparison per station along with brief descriptions for changes in each station wherever relevant (refer to Appendix A and B for detailed description and data outputs). As per the comparative analysis, the proposed scenario shows a theoretical reduction of 3.8% in time after executing or running the simulation model for ~100 hours. **For practical purposes, the major learning is that new activities related to energy efficiency strategies can be added to the main production line without impacting the weekly production rate of 8 modules completed per work week.** Such a proposed scenario is only possible after stations 5-12 undergo line balancing strategies.

Overall, the following key observations were made:

- A total time reduction of 3.8% was calculated by the proposed scenario process model. While this is a theoretical number, it is not of much practical value as it does not affect the weekly production rate of 8 modules per work week. However, **we highlight that implementing the proposed scenario would mean completing 8 modules per week**

**where the modules are already integrated with energy efficiency strategies. Furthermore, the main production line is balanced and can continuously achieve the weekly production target of 8 modules per work week.**

- Hours spent on roof build activities are reduced by 13.8%. This was achieved by re-organizing relevant roofing activities to the feeder stations that run parallel without impacting the main production line.
- High-performance envelope build does not affect the main production line as these envelope systems continue to be built and stored with high throughput in the feeder stations.
- A dedicated envelope QA/QC station (with blower door test kit and AeroBarrier tools) reduces cycle time at the station from 3 hours (baseline) to 1 hour.
- MEP activities including electrical and plumbing roughing followed by installation in utility rooms utilizes 100% of the cycle time for MEP activities from baseline.
- Solar plus storage activities utilize 86.4% of the observed downtime in stations 5-12. We can realistically assume that the remaining downtime can be available for idle time or buffer time by design.

# Case Study: ZEM Factory QA/QC

## Summary

The project team worked with KBS to develop a Zero Energy Modular (ZEM) Quality Control Protocol. The protocol provides factories guidance in the construction of high performance, zero energy standards, and can be used as an appendix to existing factory Quality Control Manuals. Building off of the existing KBS QA/QC Protocol, we integrated additional QA/QC steps needed to ensure that the EE components are appropriately installed and that the building achieves its energy performance goals.

Specifically, we provided guidance on QA/QC of high-performance envelopes, mechanical systems, duct systems, ventilation, and exhaust. We also provided relevant QA/QC program checklists to facilitate compliance with programs such as ENERGY STAR and Zero Energy Ready Homes.

## Factory Partner & Current QC protocol

KBS is a modular factory in Maine which builds a variety of building types, including single family and multifamily, to a variety of standards, including both code-minimum homes, and high-performance and zero energy buildings.

KBS has a quality assurance team which aims to meet local codes and detect any potential defects early in the process, which can serve as a cost saving measure. Furthermore, according to the Quality Control Manual (QCM) provided by KBS, the Quality Control team is also responsible for maintaining compliance with applicable codes and specifications, manufacturing operations, minimizing material waste and rework, and coordinating project activities within the department. As per the KBS QCM, the following steps are taken for quality inspection:

1. Each module has a QC traveler, which is a checklist to ensure compliance with applicable building codes and quality of workmanship.
2. Once the scope of work is completed at a workstation, the QC manager or area supervisor inspects the work and completes the checklist associated with that workstation.
3. Any discrepancies are addressed before moving the module to the next workstation. In some cases, a picture of the defect and the improved element are taken for the home records.
4. After fixing the defect, the QC manager inspects and signs off on the QC traveler as an indication that the module is ready to progress to the next production area.

The current KBS QCM does not incorporate guidance on how to build a high-performance envelope with respect to fully aligned air barriers, air sealing, thermal bridging, insulation installation, or mechanical testing. The project team's QA/QC document will be supplemental information used as reference during construction and inspection.

# Quality Control Protocol

The quality control protocol defines the acceptable level of quality and describes how the production process will ensure this level of quality in zero energy modular construction, specifically focusing on the integration of energy efficiency measures and renewable energy and storage components.

Below we provide a QC protocol for ZEM construction applicable to any modular factory producing ZEM buildings. The layout is not aligned with workstations of a specific factory. We reference our factory partners where appropriate. The intent is for a factory to integrate the proposed QC protocol to enhance their existing QA/QC procedures. The checklist items presented here are direct references from existing national QA/QC checklists, standards, and best practices and are cited as such.

## Quality Control in the Factory

Modular factories are already subject to stringent third-party monitoring of building quality. Modular construction typically has a quality enhancement program at every stage in the production process. Building materials are monitored at every stage and quality control specialists are also deployed at every stage. Modular buildings are built according to local regulations and codes where the home will be installed, similar or identical to those that apply to conventional site-built homes. A key aspect of Quality Control is ensuring that construction of the building matches engineered drawings.

QC in the Factory should include the following elements:

- Home design
- Energy evaluation
- Traveler document
- Third party inspection
- Energy inspection using a sampling protocol, such as RESNET

### Home Design Energy Evaluation

At the planning phase, quality control can be performed by modeling energy performance based on the design, using accredited energy rating software (e.g. REM/Rate™, Ekotrope, Energy Gauge). REM/Rate™ is an industry standard residential energy modeling and compliance software which is accredited by Residential Energy Services Network (RESNET). It helps to calculate heating, cooling, hot water, lighting, and appliance energy loads, consumption, and costs. The following inputs are necessary to run REM/Rate software:

1. Building type
2. Building size
3. HVAC equipment efficiency
4. Water heating efficiency
5. Appliance and lighting efficiencies
6. Envelope construction type
7. Insulation type
8. Air leakages rate
9. Number of building occupants (assumed)
10. Local climate data
11. Utility costs

Conducting a REM/Rate™ analysis early in the home's design process (e.g., pre-construction), provides builders with valuable data about the energy performance of their buildings. This can be beneficial to determine if the type of HVAC equipment, insulation type, appliances, etc. that have been selected for the building meet energy load and consumption targets.

### Traveler Documents

A traveler document is an extensive checklist used in the factory to ensure compliance with applicable building codes and quality of workmanship. Once production begins, a traveler document is assigned to each module. This inspection process scrutinizes every nuance of the day's work in relation to the module's design specifications.  Only the manager can approve the module's condition and allow it to move to the next workstation on the production line. If the inspection results are non-satisfactory then the issue is recorded on the traveler, and applicable measures are adopted to resolve it.

Most inspections are conducted visually and at the KBS factory, the current traveler includes results of 6 standard tests: water supply system test, drain waste and vent system test, hi-pot test (with/without Panel box), ground continuity test, polarity test, and operational test for standard packages.

At most factories, the current traveler does not include any additional elements related to energy efficiency components. A more comprehensive traveler document is required to ensure the quality of these aspects of the building.

Apart from the inspections and tests that are currently in practice, other tests and inspections could also be adopted in order to address the changes and evaluate the quality of EE energy strategies (Table 16). Tests should be administered as applicable to a sample of modules to verify energy performance of new designs, not as a standard QC practice on every module.

Table 16. Quality Control Tests by Energy Efficiency Strategy.

| Energy Strategies | Metrics | Definition |
|---|---|---|
| Thermal envelope | Blower door test | A blower door test helps in determining the air tightness of an envelope. A calibrated fan which is installed over a door or sealed window is used to blow the air out of unit. This will create a pressure difference between the outdoor and indoor, allowing air leakages to be identified. The volume of air leakages can then be calculated as equal to the volume of air moving through fan. |
| | Thermographic test | A thermographic test involves the use of infrared video and still cameras to measure surface temperature. In this test infrared video and still cameras produce images which depict the surface heat variation, helping to identify the leakages in the building envelope. The also helps to check the effectiveness of insulation in the envelope. |
| ERV | Pressure drop test | A pressure drop test helps to determine the air friction pressure dropped at a rated mass flow rate. This pressure drop is beneficial in determining the performance of ERV. For detailed description of test set up, procedures, and operating conditions refer to ASHRAE Standard 84. |
| Heat Pump | Input rating test | An input rating test provides information regarding capability of heat pumps. Initial and final flow rate and temperature are recorded and using these parameters the efficiency and quantity of energy consumed by the heat pump can be derived. For more details regarding test procedures, set up and calculation refer to ASHRAE Standard 118.1 - 2012. |

## RESNET Sampling Protocol

This sampling protocol is based on chapter 6 of the RESNET sampling standard. Sampling is intended to provide certification that a group of new modules meets a particular threshold such as ENERGY STAR®, energy code compliance, or qualification for an energy efficiency lending program. It is based on pre-analysis of building plans meeting the intended qualification (e.g., a HERS Index threshold), and subsequent random testing and inspections of a sample set of the module built. This sampling protocol can be used as a measure of quality control in the factory to assess the performance of energy strategies mentioned in Table 16 above. The protocol adheres to the following fourteen definitions and standards:

1. Sampling - An application of Home Energy Rating process where some (not all) modules are randomly inspected and tested in order to evaluate compliance with a set of specifications.
2. Sample Set - A specific group of modules from which one or more individual modules are randomly selected for sampling controls.
3. Sampling Controls - A collection or set of required tests and inspections performed for a sample set of modules in order to confirm that the specifications have been met. Sampling controls may refer to the entire set of tests and inspections, or to a particular phase that constitutes a defined subset of those tests and inspections.
4. Failure - When one or more of the threshold specifications is not met during the testing and inspection process.
5. Initial Failure - When one or more failure(s) are first identified in a module during the sampling process.
6. Additional Failure – When additional instances of initial failure(s) are identified in one or more of the other modules in the sample set being tested or inspected.
7. The performance testing of energy strategies described in Table 16 above can be carried out in the factory. By adopting the RESNET sampling protocol, a sample set of the module built on the factory can be inspected. According to RESNET sampling controls standard 603.7, the following protocol can be implemented for random testing of modules produced.
8. At a minimum one module out of seven modules produced needs to be inspected under the surveillance of a certified rater.
9. Sampling providers may complete the sampling controls collectively on a single module or distribute the tests and inspections across several modules within a given sample set, provided the total number of individual tests and inspections meets or exceeds the minimum ratio (1:7).
10. In a metropolitan area, builders should inspect at least 7 consecutive modules without any incidence of failure.
11. A complete set of sampling controls, whether performed on a single module or spread across several modules, must be completed whether or not one or more failures are found.
12. When an "initial failure" occurs, the failed item(s) shall be tested or inspected in two additional modules selected from the same sample set.
13. When an "additional failure" occurs in one or more of the two additional modules, the failed item(s) shall be tested or inspected in the remaining four modules selected from the same sample set.
14. If the multiple "additional failures" all apply to the same failed item, the builder shall submit to 100% inspection of that failed item, for a minimum of seven homes, before resuming sampling of that item. Remaining unrelated sampling controls may be conducted on a sampled basis throughout this process.

## Sample ZEM Energy Traveler

We compiled a general checklist for ZEM construction applicable to any modular factory. The layout is not aligned with bays or workstations of a specific factory. The intent is for a factory to integrate this checklist with existing QA/QC procedures or to include the checklist as an addendum, separating the applicable QC checklist sections for each bay or workstation. The checklist items presented here are direct references from existing national QA/QC checklists, standards and best practices and are cited as such. The 'In-Factory Checklist' is comparable to 'pre-drywall' inspection required for above code programs such as ENERGY STAR for New Homes and U.S. DOE's Zero Energy Ready Homes. Some items will vary depending on what portion of the building is constructed in factory versus on-site. Any links to external sources should be verified to be the latest, current version of the resource or standard.

## Thermal Enclosure

### Fully Aligned Air Barriers

- Required at all insulation locations. An air barrier is defined as any durable solid material that blocks air flow between conditioned space and unconditioned space, including necessary sealing to block excessive air flow at edges and seams and adequate support to resist positive and negative pressures without displacement or damage. Rigid air barriers are recommended.
- Open-cell or closed-cell foam shall have a finished thickness ≥ 5.5 in. or 1.5 in., respectively, to qualify as an air barrier unless the manufacturer indicates otherwise.
- If flexible air barriers such as house wrap are used, they shall be fully sealed at all seams and edges and supported using fasteners with capsor heads ≥ 1 in. diameter unless otherwise indicated by the manufacturer. Flexible air barriers shall not be made of kraft paper, paper-based products, or other materials that are easily torn. If polyethylene is used, its thickness shall be ≥ 6 mil.
- An air barrier at the interior vertical surface of floor insulation is recommended in Climate Zones 4-8.
- Examples of supports necessary for permanent contact include staves for batt insulation or netting for blown-in insulation. Alternatively, supports are not required if batts fill the full depth of the floor cavity, even when compression occurs due to excess insulation, as long as the R-value of the batts has been appropriately assessed based on manufacturer guidance and the only defect preventing the insulation from achieving the required installation grade is the compression caused by the excess insulation.
- An air barrier is permitted to be installed at the exterior horizontal surface of the floor insulation if the insulation is installed in contact with this air barrier, the exterior vertical surfaces of the floor cavity are also insulated, and air barriers are included at the exterior vertical surfaces of this insulation.

#### ***Technical References***

1. BSC Information Sheet 401: Air Barriers—Airtight Drywall Approach
2. BSC Information Sheet 403: Air Barriers
3. BSC Information Sheet 404: Roof Design

4. BSC Information Sheet 405: Sealing Air Barrier Penetrations

### *Checklist Items*

**Floors**

- ✓ At exterior vertical surface of floor insulation and, if over unconditioned space, also at interior horizontal surface including supports to ensure alignment.

**Ceilings**

- ✓ CZ 1-3: Interior or exterior horizontal surface of ceiling insulation
- ✓ CZ 4-8: Interior horizontal surface of ceiling insulation
- ✓ All CZ: Exterior vertical surface of ceiling insulation (e.g., using a wind baffle that extends to the full height of the insulation in every bay or a tabbed baffle in each bay with a soffit vent that prevents wind washing in adjacent bays)
- ✓ Dropped ceilings / soffits below unconditioned attics, and all other ceilings

**Walls**

- ✓ All CZ: Exterior vertical surface of wall insulation
- ✓ CZ 4-8: Interior vertical surface of wall insulation
- ✓ Walls behind showers, tubs, staircases
- ✓ Walls adjoining porch roofs
- ✓ Double-walls and all other exterior walls

***Notes***

All insulated vertical surfaces are considered walls.

## Air Sealing

Unless otherwise noted below, “sealed” indicates the use of caulk, foam, or equivalent material.

### *Technical References*

- BSC 404 air sealing and framing
- BSC Information Sheet 405: Sealing Air Barrier Penetrations
- BSC Information Sheet 406: Air Sealing Windows
- BSC Information Sheet 407: Air Barriers–Tub and Shower

### *Checklist Items*

- Ducts, flues, shafts, plumbing, piping, wiring, exhaust fans, & other penetrations to unconditioned space sealed, with blocking / flashing as needed.
- Recessed lighting fixtures adjacent to unconditioned space ICAT labeled and gasketed. Also, if in insulated ceiling without attic above, exterior surface of fixture insulated to ≥ R-10.

- Above-grade sill plates adjacent to conditioned space sealed to foundation or sub-floor. Gasket also placed beneath above-grade sill plate if resting atop concrete / masonry & adjacent to conditioned space.

- Continuous top plate or blocking is at top of walls adjoining unconditioned space, and sealed.

- Drywall sealed to top plate at all unconditioned attic / wall interfaces using caulk, foam, drywall adhesive (but not other construction adhesives), or equivalent material. Either apply sealant directly between drywall and top plate or to the seam between the two from the attic above.

- Rough opening around windows & exterior doors sealed.

- In multifamily buildings, the gap between the common wall (e.g., the drywall shaft wall) and the structural framing between units sealed at all exterior boundaries.

- Doors adjacent to ambient conditions made substantially air-tight with weatherstripping or equivalent gasket.

## Insulation

- Include this checklist item at all workstations where insulation is being installed.

- Few installation defects, only very small gaps around wiring, electric outlets, etc. and incomplete fill amounts to 2% or less. Gaps running clear through the insulation amount to no more than 2% of the total surface area covered by the insulation. Wall cavity insulation is enclosed on all six sides and in substantial contact with the sheathing material on at least one side (interior or exterior) of the cavity.

### *Technical References*

- BSC Information Sheet 501: Installation of Cavity Insulation

- ENERGY STAR Technical Bulletin: Achieving Grade-I Insulation in Fire-Rated Roofs
- ANSI/RESNET/ICC Standard 301: Normative Appendix A – Inspection Procedures for Insulation Grading and Assessment

### *Checklist Items*

- Install insulation to meet Insulation Installation Grade 1 as per ANSI/RESNETICC Standard 301.

## Thermal Bridge Reduction

These strategies may be deployed as appropriate to reduce heat loss through lumber and other non-insulation framing materials.

### *Checklist Items*

- ✓ Ceilings: For insulated ceilings with attic space above (i.e., non-cathedralized), Grade I insulation extends to the inside face of the exterior wall below.
- ✓ Walls: One or more of the following strategies:
  - a. Continuous rigid insulation, insulated siding, or combination of the two
  - b. Structural Insulated Panels, Insulated Concrete Forms, or double-wall framing
  - c. Advanced framing, including:
    - i. Corners insulated ≥ R-6 to edge
    - ii. Headers above windows & doors insulated ≥ R-3 for 2x4 framing or equivalent cavity width, and ≥ R-5 for all other assemblies (e.g., with 2x6 framing)
    - iii. Framing limited at all windows & doors to one pair of king studs, plus one pair of jack studs per window opening to support the header and sill,
    - iv. Interior / exterior wall intersections insulated to same R-value as rest of exterior wall
    - v. Minimum stud spacing of 16 in. o.c. for 2x4 framing in all Climate Zones and, in CZ 6-8, 24 in. o.c. for 2x6 framing.
- ✓ Slabs: Complete slab edge insulated and aligned with the thermal boundary of the walls.

## Mechanical Systems

### Heating and Cooling Equipment

### *Technical References*

- ANSI / RESNET / ACCA Std. 310 – see Chapter 6, Task 3: Evaluation of the Blower Fan Volumetric Airflow.

### *Checklist Items*

- ✓ Blower fan volumetric airflow is Grade I or II per ANSI / RESNET / ACCA Std. 310.
- ✓ Blower fan watt draw is Grade I or II per ANSI / RESNET / ACCA Std. 310.
- ✓ Refrigerant charge is Grade I per ANSI / RESNET / ACCA Std. 310.

## Duct Systems

Applies to heating, cooling, ventilation, exhaust, and pressure balancing ducts.

### *Technical References*

- ANSI / RESNET / ACCA Std. 310 – see Chapter 5, Task 2: Evaluation of the Total Duct Leakage

- BSC Information Sheet 604 – Transfer Ducts and Grilles

### Checklist Items

- Ducts should be located inside the enclosure air barrier.
- Ductwork installed without kinks, sharp bends, compressions, or excessive coiled flexible ductwork.
- Bedrooms pressure-balanced (e.g., using transfer grilles, jump ducts, dedicated return ducts, undercut doors) to achieve a measured pressure differential ≥ -3 Pa and ≤ +3 Pa with respect to the main body of the house when all air handlers are operating.
- Measured total duct leakage meets one of the following two options:
- Rough-in: The greater of ≤ 4 CFM25 per 100 sq. ft. of CFA or ≤ 40 CFM25, with air handler & all ducts, building cavities used as ducts, & duct boots installed. All duct boots sealed to finished surface.
- Final: The greater of ≤ 8 CFM25 per 100 sq. ft. of CFA or ≤ 80 CFM25, with the air handler & all ducts, building cavities used as ducts, duct boots, & register grilles atop the finished surface (e.g., drywall, floor) installed.
- Measured duct leakage to outdoors the greater of ≤ 4 CFM25 per 100 sq. ft. of CFA or ≤ 40 CFM25.
- If duct systems are not tested, visually verify that all seams and connections are sealed with mastic or metal tape and all duct boots are sealed to floor, wall, or ceiling using caulk, foam, or mastic tape.

#### Notes

- Item 1 - Kinks are to be avoided and are caused when ducts are bent across sharp corners such as framing members. Sharp bends are to be avoided and occur when the radius of the turn in the duct is less than one duct diameter. Compression is to be avoided and occurs when flexible ducts in unconditioned space are installed in cavities smaller than the outer duct diameter and ducts in conditioned space are installed in cavities smaller than inner duct diameter. Ducts shall not include coils or loops except to the extent needed for acoustical control.

- Item 2 - Does not apply to ventilation ducts, exhaust ducts, or non-ducted systems. For an HVAC system with a multi-speed fan, the highest design fan speed shall be used when verifying this requirement. For an HVAC system with multiple zones, this requirement shall be verified with all zones calling for heating or cooling simultaneously;

additional testing of individual zones is not required. When verifying this requirement, doors separating bedrooms from the main body of the house (e.g., a door between a bedroom and a hallway) shall be closed and doors to rooms that can only be entered from the bedroom (e.g., a closet, a bathroom) shall be open. As an alternative to the ± 3 Pa limit, a Rater-measured pressure differential ≥ -5 Pa and ≤ +5 Pa is permitted to be used for bedrooms with a design airflow ≥ 150 CFM. The Rater-measured pressures hall be rounded to the nearest whole number to assess compliance.

- Item 3 & 4 - Generally apply to the ducts of space heating, space cooling, and dwelling unit mechanical ventilation systems.

- Item 3a - Cabinets (e.g., kitchen, bath, multimedia) or ducts that connect duct boots to toe-kick registers are not required to be in place during the 'rough-in' test.

- Item 3b - Registers atop carpets are permitted to be removed and the face of the duct boot temporarily sealed during testing. In such cases, visually verify that the boot has been durably sealed to the subfloor (e.g., using duct mastic or caulk) to prevent leakage during normal operation.

## Mechanical Ventilation Systems

As defined by ANSI / RESNET / ICC Std. 301-2019, a Dwelling Unit Mechanical Ventilation System is a ventilation system consisting of powered ventilation equipment such as motor-driven fans and blowers and related mechanical components such as ducts, inlets, dampers, filters and associated control devices that provides dwelling-unit ventilation at a known or measured airflow rate.

Mechanical Ventilation System air flows and local exhaust air flows should be determined and documented using ANSI / RESNET / ICC Std. 380, including all Addenda and Normative Appendices.

### *Technical References*

- ANSI / RESNET / ICC Std. 380 – Standard for Testing Airtightness of Building, Dwelling Unit, and Sleeping Unit Enclosures; Airtightness of Heating and Cooling Air Distribution Systems; and Airflow of Mechanical Ventilation Systems.

- BSC Information Sheet 606: Placement of Intake and Exhaust Vents

### *Checklist Items*

- ✓ Measured ventilation rate is within either ± 15 CFM or ±15% of design report value.
- ✓ For any outdoor air inlet connected to a ducted return of the HVAC system, complete if present:

        a. Controls automatically restrict airflow using a motorized damper during vent. off-cycle and occupant override
        b. Measured ventilation rate is ≤ 15 CFM or 15% above design value at highest HVAC fan speed

- ✓ System fan rated ≤ 3 sones if intermittent and ≤ 1 sone if continuous.
- ✓ If Ventilation System controller operates the HVAC fan, then HVAC fan operation is intermittent and either the fan type is ECM / ICM or the controls will reduce the run-time by accounting for HVAC system heating or cooling hours.
- ✓ If ventilation air inlet location was specified in design:
    a. Air inlet pulls ventilation air directly from outdoors;
    b. Is ≥ 2 ft. above grade or roof deck; and ≥ 3 ft. distance from dryer exhausts and sources exiting the roof;
    c. Inlet is provided with rodent / insect screen with ≤ 0.5 inch mesh.

***Notes***

- If an outdoor air inlet connected to a ducted return is used as a dedicated source of outdoor air for an exhaust ventilation system (e.g., bath fan), the outdoor airflow must be automatically restricted when the exhaust fan is not running and in the event of an override of the exhaust ventilation system.

- When assessing the ventilation rate, the highest HVAC fan speed applicable to ventilation mode shall be used (e.g., if the inlet only opens when the HVAC is in 'fan-only' mode, then test in this mode). If the inlet has a motorized damper that only opens when the local mechanical kitchen exhaust is turned on, then testing is not required

## Local Mechanical Exhaust

In each kitchen and bathroom, a system is installed that exhausts directly to the outdoors and meets one of the following measured airflow and manufacturer-rated sound level standards.

### *Technical References*

- ANSI / RESNET / ICC Std. 380 – Standard for Testing Airtightness of Building, Dwelling Unit, and Sleeping Unit Enclosures; Airtightness of Heating and Cooling Air Distribution Systems; and Airflow of Mechanical Ventilation Systems.

### *Checklist Items*

- ✓ Kitchen
    a. Continuous Rate
        i. Airflow: ≥ 5 ACH, based on kitchen volume
        ii. Sound: Recommended: ≤ 1 sone
    b. Intermittent Rate:
        i. Airflow: ≥ 100 CFM and, if not integrated with range, also ≥ 5 ACH based on kitchen volume

        ii. Sound: Recommended: ≤ 3 sones

- ✓ Bath
  - a. Continuous Rate
    - i. Airflow: ≥ 20 CFM
    - ii. Sound: Recommended: ≤ 1 sone
  - b. Intermittent Rate:
    - i. Airflow: ≥ 50 CFM
    - ii. Sound: Recommended: ≤ 3 sones

## Filtration

### *Checklist Items*

- MERV 6+ filter(s) installed in each ducted mech. system, located to facilitate occupant access & regular service.

- Filter access panel includes gasket and fits snugly against exposed edge of filter when closed to prevent bypass.

- All return air and mechanically supplied outdoor air passes through filter prior to conditioning.

### *Notes*

- Item 1 - While filters are recommended for mini-split systems, HRV's and ERV's, these systems, ducted or not, typically do not have MERV-rated filters available for use.

- Item 2 - Sealing mechanisms comparable to a gasket are also permitted to be used. The filter media box (i.e., the component in the HVAC system that houses the filter) may be either site-fabricated by the installer or pre-fabricated by the manufacturer to meet this requirement. These requirements only apply when the filter is installed in a filter media box located in the HVAC system, not when the filter is installed flush with the return grill.

# Checklist References

## RESNET Sampling Protocol

1. **RESNET Sampling Protocol- Chapter Six**

## National Checklist Sources

1. **ENERGY STAR National Rater Field Checklist_Rev11.pdf**
2. **Building America QC_Checklist.pdf**

## Technical Documents

### Fully Aligned Air Barriers

1. BSC Information Sheet 401: Air Barriers—Airtight Drywall Approach

2. BSC Information Sheet 403: Air Barriers

3. BSC Information Sheet 404: Roof Design

4. BSC Information Sheet 405: Sealing Air Barrier Penetrations

5. BSC Information Sheet 406: Air Sealing Windows

6. BSC Information Sheet 407: Air Barriers–Tub and Shower

7. BSC Information Sheet 408: Critical Seal (Spray Foam at Rim Joist)

### Insulation

1. BSC Information Sheet 501: Installation of Cavity Insulation
2. ENERGY STAR Technical Bulletin: Achieving Grade-I Insulation in Fire-Rated Roofs
3. ANSI/RESNET/ICC Standard 301, Normative Appendix A – Inspection Procedures for Insulation Grading and Assessment

### Mechanical Systems

1. ANSI / RESNET / ACCA Std. 310 – Standard for Grading the Installation of HVAC Systems
2. ANSI / RESNET / ICC Std. 380 – Standard for Testing Airtightness of Building, Dwelling Unit, and Sleeping Unit Enclosures; Airtightness of Heating and Cooling Air Distribution Systems; and Airflow of Mechanical Ventilation Systems.
3. BSC Information Sheet 604 – Transfer Ducts and Grilles
4. BSC Information Sheet 606: Placement of Intake and Exhaust Vents

# Quality Assurance Traveler - Current

The following page contains the existing Quality Assurance Traveler checklist from page 44 of the KBS. Quality Assurance Manual dated 3/22/21.

**QUALITY ASSURANCE TRAVELER** (Page1 of 3)

**INSPECTION RECORD** (Page #1/ Front)

**ON LINE DATE:** ____________________

**OFF LINE DATE:** ____________________

**BUILDER:** ____________________

**Serial #** ____________________

**Model #** ____________________

**NUMBER & RECORD DISCREPANCIES ON DISCREPANCY LOG IF NOT IN STATION (See Reverse side)**

|  | Category | Discpty No. | Accepted by |
|---|---|---|---|
| Bay 1 | Specified Material & Dim |  |  |
|  | Main Floor Assembly, Deck Install |  |  |
|  | Hangers/Ledgers Install |  |  |
|  | QC Inspector |  |  |
| Bay 2 | Floor Wiring (rough electrical) |  |  |
|  | Heat Loop or Radiant Rough In (if applicable) |  |  |
|  | Heat Loops, HWBB |  |  |
|  | Rough Plumbing, |  |  |
|  | Inst. Jst hngrs & ledgers |  |  |
|  | Rim Joist Insulation |  |  |
|  | QC Inspector |  |  |
| Bay 3 | Interior Wall Construction/Installation |  |  |
|  | Exterior Wall Construction/Installation |  |  |
|  | QC Inspector |  |  |
| Bays 4 - 8 | Tub/Shower Installation/Inspect |  |  |
|  | Fixture Vents/Supply Lines (rough plumb) |  |  |
|  | Fire and Draft Stop Plumbing |  |  |
|  | Wall Wiring (rough electrical) |  |  |
|  | Fire Place Installation |  |  |
|  | Roof Constr./Insulated |  |  |
|  | Roof Installation |  |  |
|  | Rough Electrical Roof |  |  |
|  | Stair/surround wall-installation |  |  |
|  | Underlayment where required |  |  |
|  | Vent Connections at ceiling & roof |  |  |
|  | Final Insulation adjustment |  |  |
|  | Duct install, Bath fans, Range hood etc... |  |  |
|  | QC Inspector |  |  |

| TEST ELECTRICAL | Test o.k. | Test Failed | Retest o.k. |
|---|---|---|---|
| Dielectric (Hypot) 1080v./second |  |  |  |
| Continuity Operational test |  |  |  |
| Operation Polarity test/lights |  |  |  |
| Operational Polarity test/rec. |  |  |  |
| Operational Test |  |  |  |
| Tested by: |  |  |  |

|  | Category | Discpty No. | Accepted by |
|---|---|---|---|
| Bays 5 - 10 | Drywall Installed at ceiling |  |  |
|  | Drywall Installed at walls |  |  |
|  | Decking at 2nd floor where required |  |  |
|  | Sheathing (roof) |  |  |
|  | Roof Components Inventoried |  |  |
|  | Shingle Installation, Ice and Water Shield |  |  |
|  | Sheathing Walls |  |  |
|  | QC Inspector |  |  |
| Bays 10 - 15 | Window and Door Installation |  |  |
|  | Exterior Siding Installation |  |  |
|  | Electrical Installation |  |  |
|  | Panel Box, prep breakers, wiring |  |  |
|  | Heat Installation |  |  |
|  | Molding/Trim/Interior doors Installed |  |  |
|  | Handrails and balusters, Stairs |  |  |
|  | Wall Cabinets |  |  |
|  | Base Cabinets Installed, counter tops |  |  |
|  | Fire and Draft Stop Sheetrock |  |  |
|  | Plumb Fixture, drain vent, waterline, connection |  |  |
|  | Stool Installation |  |  |
|  | Appliance Installation |  |  |
|  | Tight Fitted Elect. Boxes |  |  |
|  | Shelving, kick plates, bath fixtures, paint trim |  |  |
|  | Range Hood Installation |  |  |
|  | Mantle and Surround |  |  |
|  | Correct Floor Covering |  |  |
|  | Misc. Item |  |  |
|  | QC Inspector |  |  |

**Q.A. Final Acceptance** **Date**

|  | Category | Discpty No. | Accepted by |
|---|---|---|---|
| Factory Completed $H_2O$ & DWV Plumbing Tests | See Plumbing Addendum (pg 3of3) (specific tested items) |  |  |
|  | Factory Complete water line test @ 125 psi (30 Min) |  |  |
|  | 2nd and 3d floor |  |  |
|  | Witness |  |  |
|  | DWV Test (5 psi @ 15 min/all Drains & vents) |  |  |
|  | Fixture Test |  |  |
|  | Whirl Pool Inspection / Test if applicable |  |  |
|  | QC Inspector |  |  |

|  | Test Record | Test o.k. | Retest o.k. | Witness | QC Note |
|---|---|---|---|---|---|
| HWBB | 15 Min. *100 psi (ME) |  |  |  |  |
|  | 30 Min. 125 psi (MA) |  |  |  |  |
|  | 30 Min. 100 psi (NH) |  |  |  |  |

|  | Category | Discpty No. | Accepted by |
|---|---|---|---|
| Tub/Shower diverter | Test Record |  |  |
|  | 100 psi@ 15 minutes (ME) |  |  |
|  | 100 psi@ 30 minutes (NH) |  |  |
|  | 125 psi@ 30 minutes (MA) required |  |  |
|  | QC Inspector |  |  |
| Bays 16-19 (Yard Docks) | Load Shiploose/Interior |  |  |
|  | Shipment Prep/Shiploose |  |  |
|  | All incompleted work Listed on back (pg 2 of 2) |  |  |
|  | Final Testing electrical |  |  |
|  | Final Testing DWV /Water/ H2O |  |  |
|  | Final Testing HWBB |  |  |
|  | Misc. |  |  |
|  | QC Inspector |  |  |

|  | Label Type/ Location | Applied. | Per Plan (Y/N) |
|---|---|---|---|
| LABEL APPLICATION | Datq Plate (Location:________________) |  |  |
|  | TRA Label |  |  |
|  | State Label (If applicable) |  |  |
|  | ME State Warrantee |  |  |
|  | Misc |  |  |

## KBS Builders Inc.; Plant #1 QC Traveler Checklist

All incompleted work Listed on back (pg 2 of 2)

See Plumbing Addendum (pg 3 of 3) (specific tested items)

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Date Printed: 3/22/21

# Appendices

# Appendix A Baseline Factory Processes

Appendix A provides a detailed description of the current layout and processes at the KBS facility, the project's modular factory partner.

## Main Production Line Workstations

### Component Shop (Bay 0)

All component parts are built in Bay 0 – Component Shop. Necessary components such as walls, dormers, roof assemblies, and porches are built using approved plans. Sales orders are checked for type and thickness of exterior sheathing(s) and exterior sheathing is installed in accordance with the approved fastening schedule. Sales orders are checked for exterior finishes and exterior finishes are installed in accordance with approved fastening schedules and manufacturer installation instructions. The area lead provides initial inspection. Quality control provides final inspection prior to component assemblies advancing to loading area or Job site. Quality control also inspects and documents all work performed in this area.

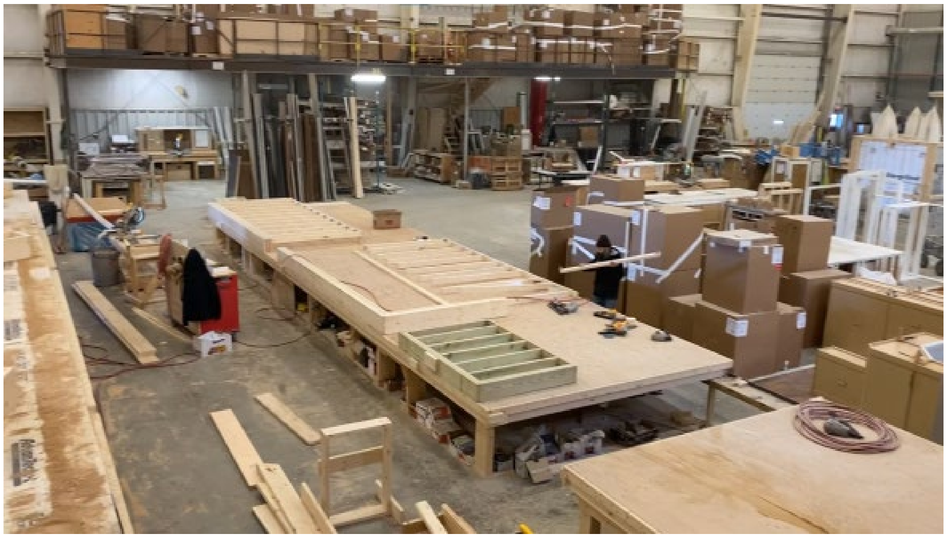

Figure A1. Bay 0 - Component parts

Table A1. Component Parts Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Component parts | 2 | 11.6 |

## Floor Framing and Decking (Bays 1a and 1b)

Floor framing and decking is performed in Bays 1a and 1b. Staples in band joist components are stitched to box length. According to plan, cut and saw components (i.e., rails, joists, opening bucks and blocking) are laid out. Floor joists and other framing members are attached in accordance with approved fastening schedule. Two spice blocks are installed as required to face the inside band joists using adhesive and fasteners in accordance with approved fastening schedule. To complete double rails, in accordance with the approved fastening schedule, outside band joists are applied. Diagonal dimensions for square are checked and adjusted as necessary. Floor decking, in accordance with the approved fastening schedule, is applied using fasteners and adhesives. Necessary holes and opening in decking are cut. Sand decking joints are made if required. To prepare floor for lifting onto raised jig, lifting hooks are installed. Upon completion of these steps, the work must be inspected by area foreman, and if any deficiencies are identified, they must be noted on the QC Travel checklist. If no deficiencies exist, or if the noted deficiencies have been corrected, the deck is ready to be moved to the next line station.

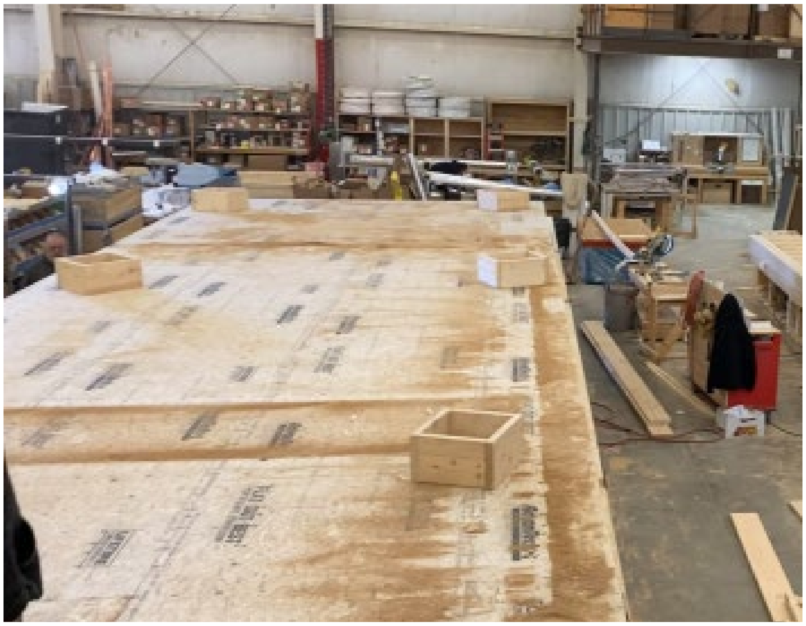

Figure A2. Bay 1 - Floor Framing and Decking

Table A2. Floor Framing and Decking Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Floor framing and decking | 3 | 17.4 |

## Raised Plumbing/Electrical Jig (Bays 2a and 2b)

Raised plumbing and electric jig work is done in Bays 2a and 2b. Firstly, the underside of deck is checked for missed nails through decking. If nails are missed, they are removed, and new nails are applied. Joist hangers or 2 bearing ledgers are installed and nailed as specified on plans. Using the approved electrical plan, electrical wires and/or fixtures are installed. The drain, waste, and vent system and potable supply lines are installed as required using the approved plumbing plan. Copper or PEX for heat loops is installed, as required per plan. The plumbing department lead-person provides initial inspection prior to unit advancing to next line station. Electrical department lead-person provides initial inspection prior to unit advancing to next line station. Quality control provides final inspection of all work performed in this area.

Figure A3. Bay 2 - Raised Plumbing/Electrical Jig

Table A3. Raised Plumbing / Electrical Jig Workstation Performance

| Workstation | # Employees | Manhours/Work station/Module |
|---|---|---|
| Raised plumbing / electrical jig | 3 | 17.4 |

## Exterior and Mate Wall Set (Bays 3 and 4)

Exterior and Mate Wall Set work is done in Bays 3 and 4. Protective floor covering over entire unit is applied. The exterior sidewall is set on unit and attached in accordance with approved fastening schedule. Exterior end walls are set on unit and attached in accordance with approved fastening schedule. The interior Mate wall is set in unit and attached in accordance with approved fastening schedule. Uplift straps are applied as required, in accordance with the approved fastening schedule. For field applied filler strips, decking at mate wall opening areas is marked and cut-back. Quality control inspects all work performed in this area.


Figure A4. Bay 3 - Exterior and Mate Wall Set

Table A4. Exterior and Mate Wall Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Exterior and mate wall set | 4.5 | 26.1 |

## Interior Partition Set (Bay 4)

Interior Partition Set work is performed in Bay 4. The floor is marked for layout of interior partitions per approved plan. Interior partitions are set and fastened to deck in accordance with approved fastening schedule. Wall tie plates are installed at the top of interior partitions to perimeter walls. Walls are joined together with the approved fastening schedule. Wall-to-wall and wall-to-floor intersections are taped. Siga Majpell installed on the wall framing table. Interior and exterior wall studs are drilled in preparation for rough plumbing and electrical, in accordance with approved practice. Electrical wires and/or fixtures are installed as required, using the approved electrical plan. Protective plates are applied as necessary for electrical wires. The electrical department lead-person provides initial inspection prior to unit advancing next line station. Quality control provides final inspection of all work performed in this area.

Figure A5. Bay 4 – Interior Partition Set

Tabe A5. Interior Partition Set Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Interior Partition Set | 4.5 | 26.1 |

## Rough Electrical and Plumbing (Bay 5)

Rough electrical and plumbing work is done in Bay 5. Electrical wires and/or fixtures are installed using the approved fastening schedule. Protective plates are applied as necessary for protection of mechanical, conduits, electrical cables, and plumbing pipes. DWV and potable supply lines are installed as required, using the approved plumbing plan. Tub and shower units are installed per approved plan in accordance with manufacturers installation instructions. Insulation is installed as required in interior partitions in accordance with approved fastening schedule. Plumbing department lead-person provides initial inspection prior to unit advancing to next line station. The electrical department lead-person provides initial inspection prior to unit advancing to next line station. Quality control provides final inspection of all work performed in this area.

Figure A6. Bay 5 - Rough Electrical and Plumbing

Table A6. Rough Electrical and Plumbing Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Rough electrical and plumbing | 5 | 29 |

## Rough Electrical and Plumbing, Drywall, and Roof Set (Bay 6)

The rough electrical and plumbing, drywall, and roof set workstation is in Bay 6. Drywall is installed on the interior face of walls as required in accordance with approved fastening schedule. The roof/ceiling assembly is lifted and set on top of module. The location is adjusted to precisely match the walls below and then the assembly is attached using the approved fastening schedule. Uplift straps are applied as required in accordance with the approved fastening schedule. Electrical wires and/or fixtures are installed as required using the approved electrical plan. Protective plates are applied as necessary for the protection of mechanical, conduits, electrical cables, and plumbing pipes. Plumbing vents are extended and/or installed as necessary per the approved plumbing plan. As required per approved plans, HVAC ductwork is installed. The plumbing department lead-person provides initial inspection prior to commencement of roof sheathing. The electrical department lead-person provides initial inspection prior to commencement of roof sheathing. Quality control provides final inspection of all work in this area prior to commencement of roof sheathing. Quality control provides final inspection of all work performed in this area.

Figure A7. Bay 6 - Rough Electrical and Plumbing, Drywall, and Roof Set.

Table A7. Rough Electrical and Plumbing, Drywall, Roof Set Workstation Performance.

| Workstation | # Employees | Manhours /Workstation/Module |
|---|---|---|
| Rough electrical and plumbing, drywall, and roof set | 5 | 29 |

## Exterior Insulation and Drywall (Bay 7)

Insulation in exterior walls and drywall are installed in Bay 7 in accordance with the approved fastening schedule. Installation of drywall continues as required in according with approved fastening schedule. The first coat of tape and mud on interior drywall surfaces are applied, and then drywall surfaces are sanded as necessary.

Table A8. Exterior Insulation and Drywall Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Exterior Insulation and Drywall | 5 | 29 |

Figure A8. Bay 7 - Exterior Insulation and Drywall.

## Exterior Insulation, Drywall Finish and Sanding (Bay 8)

The installation of insulation in exterior walls continues in Bay 8, in accordance with the approved fastening schedule. Quality control provides final inspection of all insulation installation performed in this area. A second coat of mud on interior drywall surfaces begins and is finished at this station, and final sanding of drywall surfaces begins.

Figure A9. Bay 8 - Exterior Insulation, Drywall Finish and Sanding.

Table A9. Exterior Insulation, Drywall Finish, Sanding Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Exterior Insulation, Drywall Finish, Sanding | 4.5 | 26.1 |

## Roof Sheathing, Drywall Finish and Sanding (Bay 9)

In Bay 9, the final coat of mud on interior drywall surfaces begins and is also finished. Final sanding of drywall surfaces continues and is finished as well. Lastly, proper vent is installed as required prior to commencement of roof sheathing.

Figure A10. Bay 9 Roof Sheathing, Drywall Finish and Sanding.

Table A10. Roof Sheathing, Drywall Finish, Sanding Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Roof Sheathing, Drywall Finish, Sanding | 4.5 | 26.1 |

## Roof Sheathing and Exterior Wall Sheathing (Bay 10)

In Bay 10, the sales order is checked for type and thickness of roof sheathing and installation of roof sheathing begins in accordance with approved fastening schedule. The sales order is also checked for type and thickness of exterior sheathing and exterior sheathing on exterior walls is installed in accordance with the approved fastening schedule. All window and door openings covered by sheathing are routed out. The exterior sheathing area foreman provides initial inspection prior to unit advancing to next line station. Installation of roof sheathing is then finished. Quality Control provides final inspection of all work performed in this area.

Figure A11. Bay 10 - Roof Sheathing and Exterior Wall Sheathing.

Table A11. Roof Sheathing and Exterior Wall Sheathing Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Roof Sheathing and Exterior Wall Sheathing | 5 | 29 |

## Roofing and House Wrap (Bay 11)

In Bay 11, adhesive back bitumin roof systems and/or felt roof underlayment are installed in accordance with specifications, manufacturer's instructions, and the approved fastening schedule. Drip edge is installed per specifications, and in accordance with the approved fastening schedule. The sales order is checked for type and color of roof shingles and shingles are installed in accordance with approved fastening schedule. House wrap is installed per specifications, and in accordance with manufacturer's installation instructions. The roofing department lead-person provides initial inspection prior to unit advancing to next line station. The roof is raised and hooks are installed for come-a-longs in preparation for Dry-Fit procedure, if applicable. Quality control provides final inspection of all work performed in this area.

Figure A12. Bay 11 - Roofing and House Wrap.

Table A12. Roofing and House Wrap Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Roofing and House Wrap | 5 | 29 |

## Windows & Exterior Doors, Siding, and Interior Paint (Bay 12)

In Bay 12, the sales order is checked for manufacturer and style of windows and doors. Both windows and doors are installed per plan in accordance with manufacturer's installation instructions. The sales order must be checked for manufacturer, style, and color of siding, fascia, and soffits. All those components are installed in accordance with the manufacturer's installation instructions. Protective wrap is applied to interior items prior to commencing with paint application. The first coat of interior paint is applied per specification and approved application techniques are applied. The electrical device/fixture hookup then begins as per approved plan, and manufacturer's installation instructions.


Figure A13. Bay 12 - Windows & Exterior Doors, Siding, and Interior Paint.

Table A13. Windows & Exterior Doors, Siding, and Interior Paint Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Windows & Exterior Doors, Siding, Interior Paint | 7 | 40.6 |

## Flooring, Electrical Hookups, Interior Trim (Bay 13)

In Bay 13, stairs are installed, if applicable, in accordance with the approved fastening schedule. Application of first coat of interior paint is finished with approved application techniques. Additional coats of paint are then applied per specifications. The sales order is checked for manufacturer, color, and style of cabinets, and they are installed in accordance with the approved fastening schedule. Installation of cabinets is finished in accordance with approved fastening details and schedule. The sales order is checked for manufacturer, color, and style of countertop(s), and countertop(s) are installed in accordance with the approved fastening details and schedule.

Electrical device/fixture hookup is finished as per approved plan and manufacturer's installation instructions. The electrical panel is installed in the location specified in the sales order, as per the approved electrical plan. The electrical department lead-person provides inspection of installed fixtures/devices. Installation of siding, fascia, and soffits is finished in accordance with manufacturer's installation instructions. The sales order is also checked for manufacturer, style, and color of shutters.

Shutters are installed in accordance with the manufacturer's installation instructions. Protective floor covering in area that require underlayment is removed and the area is cleaned. All debris are removed, and underlayment is installed per specifications using the approved fastening schedule. Sales order is checked for manufacturer, color, and style of interior moldings and installation of moldings begins with the approved fastening schedule. The sales order is checked for manufacturer, color, and style of flooring and installation of flooring begins with the approved fastening schedule. Come-a-longs are attached to applied hooks and the modules are dry fit to stimulate site conditions. Quality control provides final inspection of all work performed in this area.

Figure A14. Bay 13 in the back - Flooring, Electrical Hookups, Interior Trim.

Table A14. Flooring, Electrical Hookups, Interior Trim Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Flooring, Electrical Hookups, Interior Trim | 7 | 40.6 |

## Interior Trim, Electrical Tests, Plumbing Tests (Bay 14)

In Bay 14, installation of interior moldings is finished in accordance with the approved fastening details and schedule. The plumbing department performs DWV Flood Test per approved testing procedures and quality control monitors tests at least once a week. The plumbing department lead-person signs off on the test report. The electrical department performs Dielectric Strength test per the approved testing procedure and quality control must monitor test at least once a week. The electrical department also performs the GFCI and Functionality Test per approved testing procedures and quality control monitors this test once a week as well. Electrical department lead-person signs off on test report. Final drywall touch-ups are completed, and final touch-up paint begins. Quality control provides final inspection of all work performed in this area.

Figure A15. Bay 14 - Interior Trim, Electrical Tests, Plumbing Tests.

Table A15. Interior Trim, Electrical Tests, Plumbing Tests Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Interior Trim, Electrical Tests, Plumbing Tests | 7 | 40.6 |

## Touch-up, Exterior Wrap, Ship-Loose, and Labels (Bay 15)

Final touch-ups and preparation for shipping is done in Bay 15. Production documents all incomplete work and testing on the back of the QC traveler checklist for compliance control. Final touch-up paint is finished. Sales inspection is completed per the plan and sales order form. Final cleaning of module is completed. All shipped loose items are loaded and secured to avoid movement in transport. Quality control reviews all inspection reports and tests and provides final sign off. Quality control applies Data Plate, and all other additional labels as required, and places all shipping documents, a full set of plans, a copy of the ship loose list, and all related warranty documentation in unit at a standard location prior to shrink wrap. Third party or the designated QC inspector applies labels, once all work is complete and the final QC inspection is completed, in the locations specified on approved plans. Plastic protective wrap is applied to exterior of module, as necessary. The module is affixed to a temporary or permanent transport frame and moved to the yard.

Figure A16. Bay 15 on the left - Touch-up, Exterior Wrap, Ship-Loose, and Labels.

Table A6. Touch-up, Exterior Wrap, Ship-Loose, Labels Workstation Performance

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Touch-up, Exterior Wrap, Ship-Loose, Labels | 7 | 40.6 |

## Yard and Exterior (Bays 16 to 19)

Bays 16 through 19 are outside the facility. Here, all unfinished work is finished and tested as documented in the QC Traveler checklist. Any back-ordered items not previously placed in the module are loaded. Conditions of the module are verified. The module is affixed to 'over the road' transport frame for delivery to job site. All panelized walls or dormers are loaded for delivery to job site. All openings are sealed with protective plastic wrap and the unit is ready to be shipped. Quality control video/photo documents all modules and ships loose load materials that are ready to be shipped just prior to delivery date.

Figure A17. Bays 16-19 - Yard & Exterior Bays.

Table A17. Yard & Exterior Bays Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Yard & Exterior Bays | 5 | 29 |

## Feeder Workstations

### Mill Room/Automated Computer Driven CNC Saw

In this area, the components for floor, sidewall-partitions, ceiling-roof assemblies, and backers for electrical fixtures are cut. First, lumber is checked for moisture content which cannot exceed 19%. Then individual pieces are checked for excessive wane, cup, or bow. If there are no issues with the pieces, components are cut as directed by the plant manager. All work done in this area has to be checked by the quality control inspector and mill room sawyer. When all components are checked for quality, they then can be released to the individual department/bays.

Figure A18. Mill Room/Automated Computer Driven CNC Saw.

Table A18. Mill Room / Automated Driven CNC Saw Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Mill room / Automated driven CNC saw | 4 | 23.2 |

## Exterior and Interior Walls (Wall Tables)

At this station, cut and marked saw components (i.e. wall plates, studs, window and door bucks and blocking) are first laid out. Components are nailed using fasteners specified in the approved fastening schedule. Walls are squared and, if required, drywall and sheathing is applied in accordance with the approved fastening schedule. Then all windows and door openings covered by sheathing are routed out. Diagonal bracing is installed on the interior partitions. All walls are now checked by the area lead and spot-checked by QC on an ongoing basis.

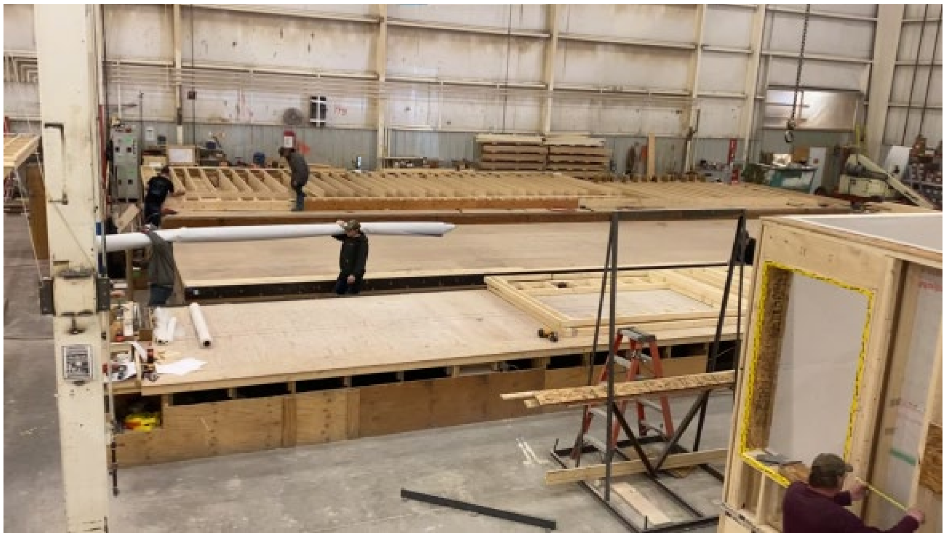

Figure A19. Exterior and Interior Walls (Wall Tables).

Table A19. Wall Tables Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Wall tables | 2 | 11.6 |

## Stairs

The stairs assembly is laid out and built per the sales order specification and per approved plans. Stringers and routed skirt boards are typically cut by the CNC Saw. The area lead provides initial inspection. Quality control provides final inspection prior to component assemblies advancing to loading area or Job site. Quality control also inspects and documents all work performed in this area.

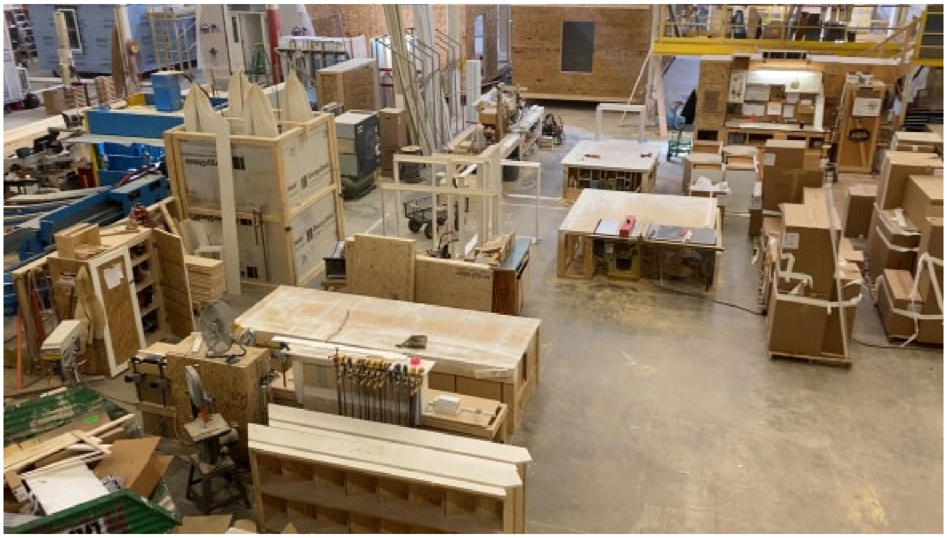

Figure A20. Stairs Workstation.

Table A20. Stairs Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Stairs | 1 | 5.8 |

## Ceiling/Roof Framing and Insulation (Drywall Jig)

Ceiling/roof framing and insulation is performed in the drywall jig area. First, workers cut and mark all of the components, as specified on approved plans (sub-fascia, rails, joists, trusses, blocking, etc.), and then the components laid out. Components are attached in accordance with the approved fastening schedule. Ceiling/roof assembly is checked for square using diagonal measurements and adjusted if necessary. The plan is checked to see if LVL or header material is needed. If applicable, LVL or header material is installed in accordance with the approved fastening schedule. Blocking for electrical fixtures or soffits is installed as required per approved plan. Roof framing area lead provides initial inspection prior to assembly advancing to be set. Quality control provides final inspection of all work performed in this area. For the drywall jig, vapor retarder is applied, furring channel is installed as applicable, and ceiling bearing shims and gypsum ceiling boards are installed to framing.

Figure A21. Ceiling/Roof Framing and Insulation (Woodroof Table & Drywall Jig).

Table A21. Woodroof Table and Drywall Jig Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Woodroof table and drywall jig | 8 | 46.4 |

## Door Shop

All interior door frames and interior trim are cut and fit where possible. Quality control provides final inspection of all work performed in this area.

Table A22. Door Shop Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Door shop | 8 | 46.4 |

## Paint/Stain Shop

Using OSHA approved safety practices, all doors and moldings are prepared and painted or stained in this area. Quality control provides final inspection of all work performed in this area.

Tale A22. Paint / Stain Shop Workstation Performance.

| Workstation | # Employees | Manhours/Workstation/Module |
|---|---|---|
| Paint / stain shop | 4 | 23.2 |

# Tooling per department

## 1: Mill Room

| Tools & Equipment | Quantity |
|---|---|
| Jig saw | 1 |
| Drill | 1 |
| Stapler | 1 |
| Miter saw | 1 |
| Table saw | 1 |
| Circular saw | 1 |
| Battery | 1 |

## 2: Bottoms

| Tools & Equipment | Quantity |
|---|---|
| Framing nail gun | 8 |
| Wide mouth staple gun | 2 |

## 3: Rough Electrical

| Tools & Equipment | Quantity |
|---|---|
| Drills | 12 |
| Circular saw | 2 |
| Impact driver / drill | 3 |
| Hole hog | 2 |
| Sawzall | 1 |
| Wide mouth staple gun | 1 |
| Batteries | 5 |

## 4: Rough plumbing

| Tools & Equipment | Quantity |
|---|---|
| Drills | 7 |
| Sawzall | 2 |
| PEX tool | 2 |
| Batteries | 2 |

## 5: Walls

| Tools & Equipment | Quantity |
|---|---|
| Cordless framing gun | 5 |
| Framing gun | 6 |
| Coil gun | 2 |
| Sawzall | 4 |
| Impact driver/drill | 7 |
| Wide mouth staple gun | 7 |
| Paper stapler | 8 |
| Sheathing gun | 1 |
| Multi tool | 2 |
| Chop saw | 1 |
| Router | 1 |
| Light | 1 |
| Batteries | 3 |

## 6: Components

| Tools & Equipment | Quantity |
|---|---|
| Framing gun | 8 |
| Drill | 4 |
| Stapler | 11 |
| Sawzall | 2 |
| Router | 1 |
| Jig saw | 1 |
| Joist hanger gun | 1 |
| Circular saw | 2 |
| Impact driver / drill | 3 |
| Roofing gun | 1 |

## 7: Insulation

| Tools & Equipment | Quantity |
|---|---|
| Wide mouth stapler | 4 |
| Paper stapler | 7 |
| Impact driver / drill | 1 |
| Insulation machines | 3 |

## 8: Drywall

| Tools & Equipment | Quantity |
|---|---|
| Router | 2 |
| Drywall drill | 12 |
| Light | 6 |
| Roto zip | 3 |
| Multi tool | 2 |
| Batteries | 1 |
| ½" mix drill | 1 |
| Mud Pump | 1 |
| Sander | 1 |

## 9: Sheathing / Siding

| Tools & Equipment | Quantity |
|---|---|
| Circular saw | 4 |
| Framing nailer | 6 |
| Impact driver / drill | 1 |
| Drill | 1 |
| Pin nailer | 1 |
| Sheathing gun | 6 |
| Sawzall | 2 |
| Router | 2 |
| Staple gun | 3 |
| Chop saw | 2 |
| Batteries | 6 |
| Charger | 1 |

## 10: Trim Department

| Tools & Equipment | Quantity |
|---|---|
| Circular saw | 2 |
| 16 ga nailer | 5 |
| 18 ga nailer | 6 |
| Angled finish nailer | 2 |
| Pin nailer | 1 |
| Sander | 1 |
| Planer | 1 |
| Router | 1 |
| Drills | 2 |
| Multi tool | 1 |
| Light | 1 |
| Batteries | 1 |
| Charger | 1 |

## 11: Cabinet shop

| Tools & Equipment | Quantity |
|---|---|
| Impact driver / drill | 2 |
| Pin nailer | 6 |
| Drill | 3 |
| Sawzall | 1 |
| Light | 1 |
| Stapler | 1 |
| Cap router | 1 |
| Plug router | 2 |
| Chop saw | 1 |
| Jig saw | 1 |
| Sander | 1 |

## 12: Stairs

| Tools & Equipment | Quantity |
|---|---|
| Impact driver / drill | 2 |
| Crown stapler | 1 |
| Finish gun | 2 |
| Drill | 1 |
| Circular saw | 2 |
| Wormdrive saw | 1 |
| Jig saw | 1 |
| Router | 2 |
| Biscut cutter | 1 |
| Blade sander | 2 |
| Sawzall | 1 |
| 16 ga nailer | 2 |

## 13: Ship loose

| Tools & Equipment | Quantity |
|---|---|
| Impact driver / drill | 1 |
| Batteries | 1 |
| Charger | 1 |

## 14: House wrap

| Tools & Equipment | Quantity |
|---|---|
| Impact driver / drill | 1 |
| Wide mouth staple gun | 2 |
| Framing nailer | 2 |

## 15: Flooring

| Tools & Equipment | Quantity |
|---|---|
| Jig saw | 1 |
| Sander | 1 |
| Stapler | 3 |
| Multi tool | 1 |
| Batteries | 3 |

## 16: Floaters

| Tools & Equipment | Quantity |
|---|---|
| Impact driver / drill | 7 |
| Drill | 2 |
| Sawzall | 3 |
| Circular saw | 1 |
| Hole hog | 2 |
| Batteries | 5 |

## 17: Finish electrical

| Tools & Equipment | Quantity |
|---|---|
| Drills | 12 |
| Light | 3 |
| Jig saw | 1 |
| Rotozip | 1 |
| Hole saw | 1 |
| Knock out kit | 1 |
| Voltage amp meter | 1 |
| Batteries | 1 |
| Chargers | 3 |

## 18: Finish plumbers

| Tools & Equipment | Quantity |
|---|---|
| Impact driver / drill | 4 |
| Drill | 4 |
| Sawzall | 2 |
| PEX tool | 2 |
| Pipe cutter | 1 |
| Light | 1 |
| Compressor (Pancake) | 1 |
| Batteries | 4 |

## 19: Woodroof

| Tools & Equipment | Quantity |
|---|---|
| Framing gun | 11 |
| Sheathing gun | 2 |
| Circular saw | 1 |
| Impact driver/drill | 10 |
| Drill | 2 |
| Wide mouth stapler | 6 |
| Drywall gun | 8 |
| Cut out tools | 2 |
| Sawzall | 4 |
| Chop saw | 1 |
| Palm nailer | 2 |
| Batteries | 9 |
| Chargers | 3 |

## 20: Paint

| Tools & Equipment | Quantity |
|---|---|
| Lights | 7 |
| K-1 heater | 2 |
| Sanders | 2 |
| Sprayers | 3 |
| Batteries | 5 |

## 21: Roofing

| Tools & Equipment | Quantity |
|---|---|
| Framing gun | 3 |
| Sheathing gun | 4 |
| Roofing gun | 2 |
| Circular saw | 3 |
| Impact driver / drill | 2 |
| Drill | 1 |
| Batteries | 4 |

## 22: Final

| Tools & Equipment | Quantity |
|---|---|
| 16 ga nailer | 2 |
| Lights | 8 |
| Vacuums | 2 |
| Heat gun | 2 |
| Batteries | 1 |
| Charger | 1 |

## 23: Service

| Tools & Equipment | Quantity |
|---|---|
| Chop saw | 1 |
| Table saw | 1 |
| Sawzall | 5 |
| Circular saw | 2 |
| Drill | 1 |
| Crown stapler | 2 |
| Biscuit jointer | 1 |
| Heat gun | 1 |
| Belt sander | 1 |
| Router | 2 |
| Compressor | 1 |
| Generator | 1 |
| Multi tool | 1 |
| Tile saw | 1 |
| Finish nailer | 2 |
| Ventilator fan | 1 |

# Appendix B Discrete Event Simulation Outputs. Integration of energy efficiency strategies into factory processes

Appendix B is the output of a discrete event simulation (DES) model create by the team of the current production process incorporating EE packages and an improved process. This appendix contains supporting information for the Case Study: Integrating Energy Efficiency Strategies into Existing Factory Processes.

Table B1. Changes Required for Energy Efficiency Packages by Station.

| **Stations** | **Time taken per station per module (in hours)** | | **Description of changes required by EE strategies** |
|---|---|---|---|
| | **Baseline Data Output** | **Proposed Scenario Data Output** | |
| Station 00 | 5.80 | 5.80 | No changes identified |
| Station 01 | 3.54 | 3.54 | No changed identified |
| Station 02A | 2.90 | 2.90 | Floor framing up into jigs – need to install insulation into rim joists at this stage<br>Additional electrical wires, conduit, or line sets for HVAC in floor system<br>Would do plumbing in floors as they will be insulated and not accessible on site |
| Station 02B | 2.90 | 2.90 | |
| Station 03 | 5.28 | 5.28 | Siga Majpell added on wall table in lieu of polyethylene – just swapping out material<br>Setting walls similar, caulking underneath walls and intersections |

| Stations | Time taken per station per module (in hours) | | Description of changes required by EE strategies |
|---|---|---|---|
| | Baseline Data Output | Proposed Scenario Data Output | |
| | | | Set twice as many walls with double 2x4 – ¾" top plate<br>Frame exterior wall on table and then interior wall on top of it, separate walls with blocking (3" blocking to create 10" thick wall) and add ¾" top plate on table (8' section)<br>Majpell smart membrane swap out from polyethylene – additional taping to ensure continuity<br>Strap and sheetrock roof system<br>Run wiring for lighting that they don't do with other modules |
| Station 04 | 5.23 | 5.23 | No changes identified |
| Station 05 | 6.52 | 6.52 | Some additional services for HVAC |
| | - | 9.5 | Solar ready activities |
| Station 06 | 6.17 | 3.67 | No roof set activity<br>Tape around electrical boxes to keep continuity of Majpell smart membrane |
| Station 07 | 7.57 | 5.80 | No roof sheathing included since the activity was moved upstream to feeder |

| Stations | Time taken per station per module (in hours) | | Description of changes required by EE strategies |
|---|---|---|---|
| | Baseline Data Output | Proposed Scenario Data Output | |
| | | | station. Effect of line balancing<br>Start mudding and taping<br>Staple insulweb to separate each stud bay<br>Staple insulweb on exterior of walls to densepack behind<br>Fire blocking every 10ft which is not required in standard wall as stud goes all the way through wall - vertical<br>Insulate densepack cellulose<br>HVAC ductwork installation<br>Running electrical up in roof system |
| | - | 0.50 | Solar roof set activity |
| Station 08 | 7.54 | 3.80 | Envelope QA/QC station (with AeroBarrier tools)<br>Flexible stations since workers move between these stations and the resources are shared. Effect of line balancing.<br>Second coat of mud<br>Final sanding of drywall<br>Installation of closed in soffit of ductwork |
| Station 09 | 6.19 | | |

| Stations | Time taken per station per module (in hours) | | Description of changes required by EE strategies |
|---|---|---|---|
| | Baseline Data Output | Proposed Scenario Data Output | |
| | | | Fire coating sheetrock behind soffit – skim coat of mud and fire tape |
| Station 10 | 5.95 | 6.50 (+2.00) | Added activities to Station 10 (utilizing 23.38% of total downtime). Since all roofing activities have moved to the floor close to roof build station, only exterior wall sheathing, and house wrap activities (performed in parallel) from baseline station 11 can be combined to station 10<br>Getting roof done – EPDM – roof curbing<br>MEP install activities in the utility room<br>Begin electrical device/fixture hookup as per approved plan, and manufacturers installation instructions.<br>if SIP panel, no need for sheathing or insulating<br>Soffit work |
| Station 11 | 7.33 | 0 | No activities. This station can be removed. |

| **Stations** | **Time taken per station per module (in hours)** | | **Description of changes required by EE strategies** |
|---|---|---|---|
| | **Baseline Data Output** | **Proposed Scenario Data Output** | |
| Station 12 | 6.69 | 5.80 | Effect of line balancing<br>Interior painting<br>Extra flashing with high performance wall – thickness, more tape and caulking<br>Siding starting |
| | | 7.30 | Home Battery Install activities. Added activities to Station 12 (utilizing 26.25% of total downtime)<br>Cabinets - typical<br>Flooring – usually not included<br>Electrical hook-ups - typical<br>Cased out windows but have extended jams so a little more time – more material swap out<br>HVAC installation of equipment happening |
| Station 13 | 6.86 | 5.95 | Effect of line balancing |
| Station 14 | 5.60 | 5.60 | Exterior condensing unit |
| Station 15 | 3.88 | 3.88 | Solar feet<br>Really loading box and punchlist<br>Load shiploose products as well |
| TOTAL | 95.95 | 92.32 | Modeled total time reduction 3.78% |

# Appendix C Discrete Event Simulation Outputs. Baseline Factory.

Appendix C contains the output of a discrete event simulation (DES) model create by the team of the current baseline factory. This appendix contains supporting information for the Case Study: Integrating Energy Efficiency Strategies into Existing Factory Processes.

Table C1. Baseline Data Output.

| Production Type | Cell Type/Cell ID (Supply, Stations, Build Tables, Storage) | Cell Entities/Cell Title | Input Unit Type (WIP %) | Output Unit Type (Unit ID, WIP %) | Input Unit Capacity in Cell (Max.) | Activity State (Work/ Idle/ NA) | Work Departments Allocation in Cell | Workers Allocation as Resources in Cell (No. of Workers by Team) | Worker Utilization | Activity Time in Cell per move by Unit (Mean, in hours) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NA | Supply | Raw materials and components for floors, dormers, and roofs | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 20 (Model assumption) | NA | Framing Dept (FD), Drilling Dept (DD) | 2 (FD=1, DD=1, Model assumption) | 100% | NA | |
| Batch Production | Storage | Raw materials and components for floors, dormers, and roofs | Stud/Lumber (Model assumption) | | Infinite (Model assumption) | Idle | | | | 0.00 (Model Assumption) | |
| | Station 00 | Components for floors, dormers, and roofs | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | 20 (Model assumption) | Idle | | | | 5.80 | |
| Primary Production Line Flow | Station 01 | Floor Framing and Decking | Stud/Lumber Batch (Model assumption) | Floor | 1 | Work | | 3 (FD=2, DD=1, Model assumption) | 61% | 3.54 | |
| | Station 02A | Raised Electrical Jig | Floor | Floor | 1 | Work | Electrical Dept (ED), QC Dept (QCD) | 3 (ED=1, QCD=1, PLD=1, Model assumption) | 100% | 2.90 | |
| | Station 02B | Raised Plumbing Jig | Floor | Floor | 1 | Work | Plumbing Dept (PLD), QCD | | | 2.90 | |
| | Storage | Floors | Floor (100%) | | 3 | | NA | | NA | 0.00 (Model Assumption) | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Batch Production | Supply | Raw materials and components for exterior walls | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 10 (Model assumption) | NA | FD | 2 (from FD) | NA | NA | |
| | Storage | Raw materials and components for exterior walls | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | Infinite (Model assumption) | Idle | | | NA | 0.00 (Model Assumption) | |
| | Build Table | Exterior Walls | Stud/Lumber Batch (Model assumption) | Exterior Wall (100%) | 2 (Model assumption) | Work | | | 100% | 2.00 (Model Assumption) | At least 2 exterior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/ shows error) |
| | Storage | Exterior Walls | Exterior Wall (100%) | | 10 (Model assumption) | Idle | NA | | NA | 0.00 (Model Assumption) | Storage for at least 10 exterior walls (Simulation method: Check when and where the model breaks/ shows error) |
| Primary Production Line Flow | Station 03 | Exterior and Mate wall Set | Floor (100%), Exterior Wall (100%) | Module (ModWIP01, 31.25%, Model assumption) | 1 (= 1 Floor + 4 Ext Walls, Model assumption) | Work | Wall Set Dept (WSD), Wrap Dept (WRPD), QCD | 4 (WSD=2, WRPD=1, QCD=1, Model | 91% | 5.28 | |

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  | assumption) |  |  |  |
| Batch Production | Supply | Raw materials and components for interior walls | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 10 (Model assumption) | NA | FD | 2 (from FD) | NA | NA |  |
|  | Storage | Raw materials and components for interior walls | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | Infinite (Model assumption) | Idle |  |  | NA | 0.00 (Model Assumption) |  |
|  | Build Table | Interior Walls | Stud/Lumber Batch (Model assumption) | Interior Wall (100%) | 2 (Model assumption) | Work |  |  | 100% | 2.00 (Model Assumption) | At least 2 interior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error) |
|  | Storage | Interior Walls | Interior Wall (100%) |  | 10 (Model assumption) | Idle | NA |  | NA | 0.00 (Model Assumption) | Storage for at least 10 interior walls (Simulation method: Check when and where the model breaks/shows error) |
| Primary Production Line Flow | Station 04 | Interior Partition Set | Module (ModWIP01, 31.25%) | Module (ModWIP02, 43.75%) | 1 (= 1 Floor + 4 Ext Walls + 4 Int Walls, | Work | WSD, DD, QCD | 4 (WSD=2, WD=1, QCD=1, Model | 90% | 5.23 |  |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Model assumption) | | | assumption) | | | |
| | Station 05 | Rough Electrical and Plumbing | Module (ModWIP02, 43.75%) | Module (ModWIP03, 50%) | Module (ModWIP03, 50%) | 1 | ED, PLD, Insulation Dept (ID), Fixtures Dept (FXD), QCD | 5 (ED=1, PLD=1, ID=1, FXD=1, QCD=1, Model assumption) | 112% | 6.52 | |
| Batch Production | Supply | Raw materials and components for roof | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 10 (Model assumption) | NA | FD | 2 (from FD) | NA | NA | |
| | Storage | Raw materials and components for roof | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | Infinite (Model assumption) | Idle | | | NA | 0.00 (Model Assumption) | |
| | Build Table | Roofs | Stud/Lumber Batch (Model assumption) | Roof (100%) | 2 (Model assumption) | Work | | | 100% | 2.00 (Model Assumption) | At least 2 roofs need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error) |
| | Storage | Roofs | Roofs (100%) | | 10 (Model assumption) | Idle | NA | | NA | 0.00 (Model Assumption) | Storage for at least 10 roofs (Simulation method: Check when and where the model breaks/shows error) |

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Primary Production Line Flow | Station 06 | Rough electrical and Plumbing, Drywall, and Roof Set | Module (ModWIP03, 50%, Model assumption) | Module (ModWIP04, 55%, Model assumption) | 1 (= 1 Floor + 4 Ext Walls + 4 Int Walls + 1 Roof, Model assumption) | Work | Drywall Dept (DWD), Roof Set Dept (RSD), ED, PLD, QCD | 5 (DWD=1, RSD=1, ED=1, PLD=1, QCD=1, Model assumption) | 106% | 6.17 | 0.50 (Roof Set) + 5.67 (Other activities) = 6.17 |
|  | Station 07 | Exterior Insulation and Drywall | Module (ModWIP04, 55%, Model assumption) | Module (ModWIP05, 60%, Model assumption) | 1 | Work | DWD, ID | 5 (DWD=4, ID=1, Model assumption) | 131% | 7.57 | Observation shows that roof set frequently happens at Station 07 |
|  | Station 08 | Exterior Insulation and Drywall Finish and Sanding | Module (ModWIP05, 60%, Model assumption) | Module (ModWIP06, 65%, Model assumption) | 1 | Work | DWD, ID, QCD | 4 (DWD=2, ID=1, QCD=1, Model assumption) | 130% | 7.54 |  |
|  | Station 09 | Roof Sheathing, Drywall Finish and Sanding | Module (ModWIP06, 65%, Model assumption) | Module (ModWIP07, 70%, Model assumption) | 1 | Work | DWD, ED, Sheathing Dept (SD) | 4 (DWD=2, ED=1, SD=1, Model assumption) | 107% | 6.19 |  |
|  | Station 10 | Roof Sheathing and exterior wall sheathing | Module (ModWIP07, 70%, Model assumption) | Module (ModWIP08, 75%, Model assumption) | 1 | Work | SD, QCD | 5 (SD=4, QCD=1) | 103% | 5.95 |  |
|  | Station 11 | Roofing and house wrap | Module (ModWIP08, 75%, Model assumption) | Module (ModWIP09, 80%, Model assumption) | 1 | Work | Roofing Dept (RD), WRPD, QCD | 5 (RD=3, WRPD=1, QCD=1, Model assumption) | 126% | 7.33 | 3.665 (Material Movement) + 2.415 (Roof Work) + 1.25 (House wrap) = 7.33 |
|  | Station 12 | Windows & Exterior Doors, Siding, and Interior Paint | Module (ModWIP09, 80%, Model assumption) | Module (ModWIP10, 85%, Model assumption) | 1 | Work | Window Door Dept (WDD), Siding Dept (SDD), | 7 (WDD=2, SDD=2, PNTD=3, Model | 115% | 6.69 |  |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Paint Dept (PNTD) | assumption) | | | |
| | Station 13 | Cabinets, Flooring, Electrical Hookups, Interior Trim | Module (ModWIP10, 85%, Model assumption) | Module (ModWIP11, 90%, Model assumption) | 1 | Work | Stairs Dept (STRD), Installation Dept (INSD), PNTD, Flooring Dept (FLRD), QCD | 7 (STRD=2, INSD=1, PNTD=2, FLRD=1, QCD=1, Model assumption) | 118% | 6.86 | |
| | Station 14 | Interior Trim, Electrical Tests, Plumbing Tests | Module (ModWIP11, 90%, Model assumption) | Module (ModWIP12, 95%, Model assumption) | 1 | Work | DWD, Testing Dept (TD), PNTD, QCD | 7 (DWD=1, TD=4, PNTD=1, QCD=1, Model assumption) | 97% | 5.60 | |
| | Station 15 | Touch-up, Exterior Wrap, Ship-Loose, and Labels | Module (ModWIP12, 95%, Model assumption) | Module (ModWIP13, 100%, Model assumption) | 1 | Work | Cleaning Dept (CD), Ship Loose Dept (SLD), WRPD, Module Set Dept (MSD) | 7 (CD=2, SLD=2, WRPD=1, MSD=2, Model assumption) | 67% | 3.88 | |

# Appendix D Discrete Event Simulation Outputs. Improved factory process factory.

Appendix D contains the output of a discrete event simulation (DES) model create by the team modeling the improved factory process. This appendix contains supporting information for the Case Study: Integrating Energy Efficiency Strategies into Existing Factory Processes.

Table D1. Improved Process Model Data Output

| Production Type | Cell Type/Cell ID (Supply, Stations, Build Tables, Storage) | Cell Entities/Cell Title | Input Unit Type (WIP %) | Output Unit Type (Unit ID, WIP %) | Input Unit Capacity in Cell (Max.) | Activity State (Work/ Idle/ NA) | Work Departments Allocation in Cell | Workers Allocation as Resources in Cell (No. of Workers by Team) | Worker Utilization | Activity Time in Cell per move by Unit (Mean, in hours) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NA | Supply | Raw materials and components for floors, dormers, and roofs | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 20 (Model assumption) | NA | Framing Dept (FD), Drilling Dept (DD) | 2 (FD=1, DD=1, Model assumption) | 100% | NA | |
| Batch Production | Storage | Raw materials and components for floors, dormers, and roofs | Stud/Lumber (Model assumption) | | Infinite (Model assumption) | Idle | | | | 0.00 (Model Assumption) | |
| | Station 00 | Components for floors, dormers, and roofs | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | 20 (Model assumption) | Idle | | | | 5.80 | |
| Primary Production Line Flow | Station 01 | Floor Framing and Decking | Stud/Lumber Batch (Model assumption) | Floor | 1 | Work | | 3 (FD=2, DD=1, Model assumption) | 61% | 3.54 | |
| | Station 02A | Raised Electrical Jig | Floor | Floor | 1 | Work | Electrical Dept (ED), QC Dept (QCD) | 3 (ED=1, QCD=1, PLD=1, Model assumption) | 100% | 2.90 | |
| | Station 02B | Raised Plumbing Jig | Floor | Floor | 1 | Work | Plumbing Dept (PLD), QCD | | | 2.90 | |
| | Storage | Floors | Floor (100%) | | 3 | | NA | | NA | 0.00 (Model | |

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  | Assumption) |  |
| Batch Production | Supply | Raw materials and components for exterior walls | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 10 (Model assumption) | NA | FD | 2 (from FD) | NA | NA |  |
|  | Storage | Raw materials and components for exterior walls | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | Infinite (Model assumption) | Idle |  |  | NA | 0.00 (Model Assumption) |  |
|  | Build Table | High-Performance Exterior Walls | Stud/Lumber Batch (Model assumption) | High-Performance Exterior Wall (100%) | 2 (Model assumption) | Work |  |  | 100% | 2.00 (Model Assumption) | At least 2 exterior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error) |
|  | Storage | High-Performance Exterior Walls | High-Performance Exterior Wall (100%) |  | 10 (Model assumption) | Idle | NA |  | NA | 0.00 (Model Assumption) | Storage for at least 10 exterior walls (Simulation method: Check when and where the model breaks/shows error) |
| Primary Production Line Flow | Station 03 | High-Performance Exterior and Mate wall Set | Floor (100%), Exterior Wall (100%) | Module (ModWIP01, 31.25%, Model | 1 (= 1 Floor + 4 Ext Walls, Model | Work | Wall Set Dept (WSD), Wrap Dept | 4 (WSD=2, WRPD=1, QCD=1, | 91% | 5.28 |  |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | assumption) | assumption) | | (WRPD), QCD | Model assumption) | | | |
| Batch Production | Supply | Raw materials and components for interior walls | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 10 (Model assumption) | NA | FD | 2 (from FD) | NA | NA | |
| | Storage | Raw materials and components for interior walls | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | Infinite (Model assumption) | Idle | | | NA | 0.00 (Model Assumption) | |
| | Build Table | Interior Walls | Stud/Lumber Batch (Model assumption) | Interior Wall (100%) | 2 (Model assumption) | Work | | | 100% | 2.00 (Model Assumption) | At least 2 interior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error) |
| | Storage | Interior Walls | Interior Wall (100%) | | 10 (Model assumption) | Idle | NA | | NA | 0.00 (Model Assumption) | Storage for at least 10 interior walls (Simulation method: Check when and where the model breaks/shows error) |
| Primary Production | Station 04 | Interior Partition Set | Module (ModWIP01, 31.25%) | Module (ModWIP02, 43.75%) | 1 (= 1 Floor + 4 Ext Walls + 4 Int | Work | WSD, DD, QCD | 4 (WSD=2, WD=1, QCD=1, Model | 90% | 5.23 | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Line Flow | | | | | Walls, Model assumption) | | | assumption) | | | |
| | Station 05 | Rough Electrical and Plumbing | Module (ModWIP02, 43.75%) | Module (ModWIP03, 50%) | Module (ModWIP03, 50%) | Work | ED, PLD, Insulation Dept (ID), Fixtures Dept (FXD), QCD | 5 (ED=1, PLD=1, ID=1, FXD=1, QCD=1, Model assumption) | 112% | 6.52 | Added activities to Station 05 (utilizing 34 17% of total downtime) |
| Primary Production Line Flow | Solar Ready | 1" PVC from mech room to roof, 1" PVC from mech room to electrical main, 2" PVC from mech room to electrical main (for battery), and conduit and/or wiring to belly/gable end | | | | Work | ED | 4 (from ED) | 100% | 9.5 | |
| Batch Production | Supply | Raw materials and components for roof | Stud/Lumber (Model assumption) | Stud/Lumber (Model assumption) | Infinite, arrival in batches of 10 (Model assumption) | NA | Sheathing Dept (SD), FD | 2 (from FD) | NA | NA | |
| | Storage | Raw materials and components for roof | Stud/Lumber (Model assumption) | Stud/Lumber Batch (Model assumption) | Infinite (Model assumption) | Idle | | | NA | 0.00 (Model Assumption) | |
| | Build Table | Roofs | Stud/Lumber Batch, Sheathing (Model assumption) | Roof including sheathing (100%) | 2 (Model assumption) | Work | | | 100% | 2.00 (Model Assumption) | At least 2 roofs need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre-set solar roofing activities | SolarDeck installed on roof, Solar feet installed on roof, and Solar rails installed on roof | Relevant resources and equipment | NA | 2 (Model assumption) | Work | Sub-contractor | 2 (Sub-contractor) | 100% | 4.5 | Added activities to Station 05 (utilizing 16 18% of total downtime). This includes material movement that is now reduced by 50% |
| | Storage | Solar Roofs | Solar Roofs (100%) | | 10 (Model assumption) | Idle | NA | | NA | 0.00 (Model Assumption) | Storage for at least 10 roofs (Simulation method: Check when and where the model breaks/shows error) |
| Primary Production Line Flow | Station 06 | Rough electrical and Plumbing, Utility room rouging, Drywall | Module (ModWIP03, 50%, Model assumption) | Module (ModWIP04, 55%, Model assumption) | 1 (= 1 Floor + 4 Ext Walls + 4 Int Walls + 1 Roof, Model assumption) | Work | Drywall Dept (DWD), Roof Set Dept (RSD), ED, PLD, QCD | 5 (DWD=1, RSD=1, ED=1, PLD=1, QCD=1, Model assumption) | 100% | 3.67 | |
| | Solar Roof Set | Same as typical roof set | NA | NA | NA | Work | NA | NA | 100% | 0.50 | Not a new activity but replacing typical roof set. Added to Station 07 before |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | the activities mentioned in row below |
| | Station 07 | Exterior Insulation and Drywall | Module (ModWIP04, 55%, Model assumption) | Module (ModWIP05, 60%, Model assumption) | 1 | Work | DWD, ID | 5 (DWD=4, ID=1, Model assumption) | 100% | 5.80 | No roof sheathing included since the activity was moved upstream. Effect of line balancing |
| | Station 08 and 09 | Exterior Insulation and Drywall Finish and Sanding | Module (ModWIP05, 60%, Model assumption) | Module (ModWIP06, 70%, Model assumption) | 1 | Work | DWD, ID, QCD | 4 (DWD=2, ID=1, QCD=1, Model assumption) | 100% | 5.80 | Flexible stations since workers move between these stations and the resources are shared. Effect of line balancing. Include Envelope QA/QC |
| | Station 10 (Post-set solar roofing activities) | Microinverters installed on roof and Solar Panels installed on roof | Module (ModWIP08, 75%, Model assumption) | Module (ModWIP09, 80%, Model assumption) | 1 | Work | Sub-contractor | 3 (from sub-contractor) | 100% | 6.50 | Added activities to Station 10 (utilizing 23 38% of total downtime) |
| | Station 10 (MEP installation activities) | Install MEP systems in the utility room | NA | NA | 1 | Work | Sub-contractor | 3 | 100% | 2.00 | ASHP, ERV, HPWH Equipment |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Exterior wall sheathing and house wrap activity added to Station 10 | House wrap | Module (ModWIP08, 75%, Model assumption) | Module (ModWIP09, 80%, Model assumption) | 1 | Work | SD, QCD | 5 (SD=4, QCD=1) | 100% | 1.00 (This will not get added to the total time in Station 10 since the activities are performed in parallel by a non-conflicting crew) | Since all roofing activities have moved to the floor close to roof build station, only exterior wall sheathing, and house wrap activity from baseline station 11 can be combined to station 10 |
| | Station 11 | No activities. This station can be removed. | | | | | | | | | |
| | Station 12 | House Wrap Windows & Exterior Doors, Siding, and Interior Paint | Module (ModWIP09, 80%, Model assumption) | Module (ModWIP10, 85%, Model assumption) | 1 | Work | Window Door Dept (WDD), Siding Dept (SDD), Paint Dept (PNTD) | 7 (WDD=2, SDD=2, PNTD=3, Model assumption) | 100% | 5.80 | Effect of line balancing |
| | Home Battery Install activities | Battery in mech room, battery gateway, and paneling for meters and disconnects on gable end | | | | Work | Sub-contractor | 2 (from sub-contractor) | 100% | 7.30 | Added activities to Station 12 (utilizing 26 25% of total downtime) |
| | Station 13 | Cabinets, Flooring, Electrical Hookups, Interior Trim | Module (ModWIP10, 85%, Model assumption) | Module (ModWIP11, 90%, Model | 1 | Work | Stairs Dept (STRD), Installation Dept | 7 (STRD=2, INSD=1, PNTD= | 105% | 5.95 | Effect of line |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | assumption) | | | (INSD), PNTD, Flooring Dept (FLRD), QCD | 2, FLRD=1, QCD=1, Model assumption) | | | balancing |
| | Station 14 | Interior Trim, Electrical Tests, Plumbing Tests | Module (ModWIP11, 90%, Model assumption) | Module (ModWIP12, 95%, Model assumption) | 1 | Work | DWD, Testing Dept (TD), PNTD, QCD | 7 (DWD=1, TD=4, PNTD=1, QCD=1, Model assumption) | 97% | 5.60 | |
| | Station 15 | Touch-up, Exterior Wrap, Ship-Loose, and Labels | Module (ModWIP12, 95%, Model assumption) | Module (ModWIP13, 100%, Model assumption) | 1 | Work | Cleaning Dept (CD), Ship Loose Dept (SLD), WRPD, Module Set Dept (MSD) | 7 (CD=2, SLD=2, WRPD=1, MSD=2, Model assumption) | 67% | 3.88 | |

# Appendix E Baseline model data collection strategy

To document the current conditions and create the baseline process model, the project team followed a multi-variable monitoring and data collection strategy. Activity duration data were gathered using a combination of expert interviews, manually documented time stamps from 'travelers', and data-collection methods using video data obtained from the KBS factory. This appendix contains supporting information for the Case Study: Integrating Energy Efficiency Strategies into Existing Factory Processes

Table E1. A Multi-variable Monitoring and Data Collection Strategy to Inform the Baseline Process Model.

| ***Priority*** | ***What?*** | ***When?*** | | ***How?*** | ***Why?*** |
|---|---|---|---|---|---|
| **High/Med/Low (H/M/L)** | **Data** | **In-Factory Home-building Stage** | **Data Fidelity/Granularity (Minimum Threshold)** | **Recommended Tools/Methods/Data Sources** | **Intended Output** |
| H | Latest factory floor plan layout | As-Planned | Single line floor plan (image/PDF is ok if no dwg). Facility dimension (perimeter) and location of door Sketch of location of workstation-mainline and feeder stations | Rough sketch, 2D or 3D CAD, BIM | Structure from Motion (SfM) |
| M | Project specifications, Product specifications, Construction details, Sub-contractors | As-Planned | Envelope and roof details, Solar PV product details, Battery product details | Bill of Quantities (BOQ)/Bill of Materials (BOM), Construction Specifications document | Product specifications as weighted constraints to baseline process model |
| M | Construction Schedule, Sub-contractors | As-Planned | Factory-built and on-site schedule, rough-in stage details, number of workers involved | Enterprise Resource Planning (ERP) | Projected Process specifications as weighted constraints to baseline process model, Inputs of Projected Lead Time, and |

| | | | | | |
|---|---|---|---|---|---|
| | | | Factory production rate (on average)<br>Workforce composition- trades, labor, and other salary employees | | Designed Cycle Time |
| H | Qualitative information | As-Planned | N/A | AEC team, Process engineer, Factory manager, Construction manager, IT team | Product and Process inputs to baseline process model, SfM |
| H | Observational/ Anecdotal information | As-Built | Collect factory photographs, Monitor, and supervise activities, perform visual inspection – subjective data collection. Intuitively reflect information pertaining spatial aspects of the construction progress and their associated complexities. | Process engineer, Factory manager, Construction manager | Product and Process inputs to baseline process model, SfM, Downtime inputs |
| H | In-Factory Activity Video | As-Built | 720p, unobstructed Field-of-View (FOV) | Wide-angle CCTV security camera feed, wall/ceiling mounted cameras, time-lapse video capturing devices | SfM, baseline process model, Location of cameras helps estimating relative camera locations and informs SfM procedure, inputs to Lead Time, Downtime inputs |
| M | Station Activity Video | As-Built | 720p, unobstructed Field-of-View (FOV) | Targeted ground-mounted/tripod-mounted cameras | SfM, Time inputs to baseline process model, Time study, inputs to productivity analysis model, inputs to Cycle Time, Downtime inputs |

| | | | | | |
|---|---|---|---|---|---|
| H | Worker Activity Point-of-View (POV) Video | As-Built | 720p, unobstructed FOV | Head-mounted GoPro (any head-mounted small camera for point-and-shoots/ camcorders) | SfM, Time inputs to baseline process model, Time-and-Motion study, inputs to productivity analysis model |
| H | 2D map of Worker Location | As-Built | Similar to average GPS time transfer data for track period of 780 nanoseconds (ns), Ok if it is featureless data and without any semantic scene information | Off-the-shelf Single ID sensor on each worker (such as WLAN sensor in Indoor WLAN Environment). Preferably on hard-hats | SfM, Time and motion-based time inputs to baseline process model, inputs to productivity analysis model, Downtime inputs |
| M | 3D map of Worker Activity | As-Built | XYZ Coordinates for each sensor | Off-the-shelf Rigid body sensors (on gloves, on belts, on-body) | SfM, Time and motion-based time inputs to baseline process model, inputs to productivity analysis model |
| L | Station Location | As-Built | Similar to average GPS time transfer data for track period of 780 ns | Inertial Measurement Units (IMUs) | Time and motion-based time inputs to baseline process model, inputs to productivity analysis model, Downtime inputs |
| H | Visually Obstructed (VO) Activity | As-Built | Visual recognition, If video - 720p, unobstructed FOV | Sensors (location, sound, proximity), observational/anecdotal evidence, Cameras (POV GoPro), IMUs | SfM, Time and motion-based time inputs to baseline process model, inputs to productivity analysis model |
| H | Daily Updated Construction Schedule | As-Built | Per work day, number of workers involved. Effectively represent multivariable progress information (i.e., schedule, cost, and performance) | Traveling data sheet at each station, Documentation of daily construction report | Inputs to baseline process model, time inputs to lead time, cycle time, Downtime inputs |

| | | | | | |
|---|---|---|---|---|---|
| M | Worker teams, sub-contractor teams | As-Built | Visual recognition | Colored hard-hats/vests for each team | Activity chunks, Schedule mapping, SfM |

# Appendix F Lean improvements to factory storage

Table F1. Distance of Storage to the Related Workstation Before and After Suggested Lean Improvements.

| Workstation | Distance before (ft) | Distance after (ft) |
|---|---|---|
| Station #0 - components | 72 | 198 |
| Station #1 - floor build | 93 | 178 |
| Station #2a / 2b - raised jigs | 9 | 9 |
| Station #3 - wall set | 54 | 51 |
| Station #4 - wall set / rough el. & plumbing | | |
| Rough plumbing | 71 | 71 |
| Exterior wall storage rack | 5 | 5 |
| Interior wall storage rack | 31 | 31 |
| Electrical wire & cable | 48 | 48 |
| Station #5 - rough el. & plumbing | | |
| Rough plumbing | 1269 | 381 |
| Electrical wire & cable | 1246 | 435 |
| Station #6 - interior drywall / roof set | 8 | 16 |
| Station #7 - installation of drywall / mud & tape | 8 | 8 |
| Station #8 - installation of drywall / mud & tape | | |
| Insulation | 28 | 28 |
| Drywall supplies | 8 | 8 |
| Station #9 - final mud tape / paint / roof vents | 28 | 28 |
| Station #10 - roof sheathing / insulation / ext. sheathing | 751 | 112 |
| Station #11 - install roofing materials / house wrap | 771 | 281 |
| Station #12 - install exterior doors / windows / siding | | |
| Pole barn (after change – from the factory) | 494 | 216 |
| Paint booth | 20 | 25 |
| Interior doors, trim, paint | 7 | 7 |
| Station #13 - install kitchens / finish electrical | | |
| Finish electrical | 86 | 86 |
| Counter tops | 119 | 318 |
| Cabinets | 49 | 316 |
| Stairs | 62 | 7 |
| Flooring | 55 | 267 |
| Station #14 - install interior trim / finish plumbing | | |
| Finish | 60 | 98 |
| Trim | 48 | 8 |
| Station #15 - install ship loose / wrap and fasten box to frame | | |
| Ship loose | 125 | 22 |
| Transport wrap | 3 | 10 |
| CNC saw | 175 | 40 |

| Workstation | Distance before (ft) | Distance after (ft) |
|---|---|---|
| Roof build | 212 | 38 |
| Raised roof jig | 61 | 19 |
| Exterior wall build | 197 | 74 |
| Interior wall build | 1519 | 295 |

EXHIBIT MR-6

# Zero Energy Modular Factory Initiative

## How to Create and Build a Zero Energy Modular (ZEM) Housing Factory Serving Affordable Housing

VEIC
128 Lakeside Ave, Suite 401
Burlington, VT, 05401
www.veic.org

April, 2019

*Made possible with funding from the New York Community Trust*

VEIC

veic.org

# Table of Contents

## Context

This report is the second volume in a two-volume series exploring the demand for and capacity to build Zero Energy Modular (ZEM) homes in New York State.

Volume 1: Market Analysis for Zero Energy Modular Homes in New York State[1] assesses the market potential, defines the technical and economic costs and benefits of a ZEM pilot, inventories current market supports such as affordable home loan products and financial incentives for energy efficient homes, and explores whether there are existing modular builders that could build ZEM and to what extent new capacity needs to be developed.

Volume 2: Zero Energy Modular Factory Initiative developed the necessary tools to enable investments in a ZEM factory and provides a foundation for interested parties to better understand how to efficiently and effectively set up and operate a ZEM factory.

Volume 1 was sponsored by NYSERDA. Volume 2 was possible with funding from The New York Community Trust. These two resources bring together all the components for successful market launch into one package that can be used in New York and beyond, to bring the ZEM solution to scale.

## Authors

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## Acknowledgments

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We would also like to thank Yestermorrow, whose prefab factory tour provided an extremely valuable opportunity to visit the major modular and panelized factories in Vermont and New Hampshire and discuss factory plans with those that run these factories.

Thank you to reviewers for their insightful comments: Michael Bautista (Boulder TEC, Boulder Valley School District, CO), Tim McCarthy (Leaf Prefab, NY), Benjamin Harrington (NYSERDA), Brady Peeks (Northwest Energy Works, Inc.), John Scicchitano (NYSERDA), and Ryan Wallace (Solar Home Factory, NY). VEIC would like to thank the staff at NYSERDA for their partnership, guidance, and feedback during the research and information gathering process for this report.

Thank you to the project funder, the New York Community Trust.

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[1] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

# Foreword

Demand for clean energy, including net zero buildings, is surging across New York State. New Yorkers recognize not only that clean energy investments are good for our health and our planet, but also that they pay off handsomely to both our state economy and to individual wallets.

NYSERDA strives to boost both the supply and the demand for clean energy products and services. Some industries have blossomed with support from NYSERDA; solar power in New York increased by more than 1,000 percent from 2011 to 2017, leveraging more than $2.8B in private investment. Other industries are nascent, with parallel opportunity for growth; Zero Energy Modular (ZEM) construction is one such industry.

ZEM is an important industry because it contributes to the state's goal of clean energy access for all residents. Over 150,000 mobile and manufactured homes are occupied today across New York State. These homes provide an affordable pathway to home ownership. However, they are often grossly inefficient, as well as unhealthy, especially as they age. Many have structural and safety issues that prevent performance-improving retrofits. ZEM provides an opportunity for these residents to reduce their net home energy consumption to zero, with a resulting positive effect on monthly bills and the overall cost of living.

Manufacturers of ZEM have made sizeable investments in ZEM construction; in 2019, the first ZEM homes rolled out of New York factories. If demand continues to grow, then much more ZEM building capacity will be needed. This manual represents the first-ever attempt to consolidate information and provide a tool-kit to current or future investors in ZEM factories. It makes an important contribution to the future of net zero energy homes in New York, to the benefit of our economy and to the residents who will live in these homes.

John Scicchitano, Director, NYSERDA

# Executive Summary- The Zero Energy Modular Factory Initiative

As construction costs soar, modular housing is an increasingly attractive option for developers and homeowners. The emergence of zero energy modular (ZEM) homes presents an opportunity to combine the cost-savings of modular construction with the benefits of zero energy. Affordable housing developers in particular face staggering challenges. Rising construction costs, labor shortages, hurdles with land acquisition and fluctuating federal and state grant and capital pools can make it costly and slow to add new, affordable units to the nation's housing stock. First cost and minimum code compliance often dominate decision-making priorities. The ZEM Factory Initiative proposes a new business model to address the shortage of affordable housing units: growth of ZEM factories to manufacture energy-efficient, affordable units, and sell them directly to affordable housing developers. In addition to providing high quality and healthy homes to those who need them most, ZEM factories can create living wage manufacturing jobs. The ZEM Factory Initiative will bring the clean energy economy to rural areas, serving as catalyst for transformation of the affordable housing market.

Zero energy modular homes are built to meet a stringent zero energy standard. A ZEM home can be built at a lower cost and a higher quality than a similar site-built home. The ZEM home model uses construction principles that result in comfortable homes, with excellent indoor air quality, durability, and low energy use. ZEM homes are generally all-electric and paired with solar panels to offset the home's energy use. ZEM homes can also include grid-connected batteries. In partnership with local utilities, these homes can be part of a grid modernization and battery storage efforts.

This document is a how-to manual that provides open source information about the ZEM Factory Initiative concept. The manual provides guidance for developing a ZEM factory, including factory plan options (size, labor requirements, costs for start-up). The manual, written as the companion piece to *Volume 1: Market Analysis for Zero Energy Modular Homes in New York State*, provides a template that could be used in New York State and nationally. We expect this manual will be interest to three primary target audiences:

### Factory Developers

This guide provides information and a toolkit that can be used to develop a business plan for a new factory, or when evolving an existing factory's production toward 100% ZEM homes. We provide a description of production steps and construction options . The guide also provides information relating to third-party certification and permitting requirements, and considerations for working with affordable housing providers.

### Affordable Housing Partners

This guide will provide affordable housing providers information on the benefits of ZEM homes, building characteristics, ZEM homes third-party certification options, expected construction timeline, and strategies that factories can employ to produce and deliver a home to income-qualified buyers.

**Funders and Social-Enterprise Investors**

This guide, along with Volume 1: *Market Analysis for Zero Energy Modular Homes in New York State*,[2] demonstrate that building factories to build ZEM homes for affordable housing providers can be done by private sector business entrepreneurs. However, some barriers remain, and support will be needed to launch this market in New York State and nationally, and to accelerate the replacement of old building stock with affordable, zero-energy housing for income-qualified residents. We present examples of projects that are ready to be launched, and next steps that will result in the launch of this market in New York State and provide zero-energy homes for New York's most vulnerable residents. For investors, ZEM factories are a mission-aligned social enterprise that is committed to reducing greenhouse gases and providing a stable long-term investment.

**ZEM Factory Minimum Requirements and Market Supports:**

- Minimum start-up funds needed to establish a ZEM factory: capital requirements will of course vary with factory size, but we estimate than a minimum of $500-700,000 will be needed to start a factory of 50-70 modules per year capacity.
- Labor requirements: we estimate that a small to medium ZEM factory would require 20-50 full-time staff.
- To ensure that production is optimized and costs remain affordable, we recommend than ZEM factories design a lean manufacturing process, and limit home customization.
- ZEM factory and housing development case studies demonstrate that the market is ready for this solution and with sufficient state support to launch a pilot, we expect ZEM housing to grow in New York in the next decade.

ZEM factory owners will need to have a steadfast commitment to serving the low-income affordable housing market and prioritize greenhouse gas savings and social and environmental impacts over high profit margins. That said, ZEM factories must be able to generate profits, provide fair wages that benefit all employees, and generate income to reinvest in the factory and trainings. ZEM homes have enormous potential to transform the housing landscape in New York, and we believe ZEM factories can be equally transformative to local economies, providing stable, living wage manufacturing jobs.

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[2] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

# Benefits of the Zero Energy Modular Concept

## Efficiencies of Modular Construction

Modular homes have several advantages when compared to on-site, stick-built construction,[3] due to being built in factories, rather than outdoors. The site-built homes are exposed to weather delays, potentially lower quality supplies, and lack of organization. Factories aim to remove or reduce these issues.

> A modular factory can be set up to create a safe, comfortable, organized, and efficient space for workers

One advantage that factories provide is a safe and efficient space for workers since the climate-controlled space can be organized much more easily than an outside space. Unlike construction sites, where weather delays are common, and tools are moved daily from a storage box or truck to the work area, modular construction takes place in a climate-controlled environment, where tools and material are systematically organized in a way to reduce waste and delays. The climate-controlled space allows workers to be comfortable regardless of the weather and ensures the long-term performance of the building material. There is also no risk that the materials will get wet or degrade due to weather or UV exposure.

Another advantage is the speed at which modular homes can be built once the workforce has been trained for specific tasks, leading them to quickly become efficient at those tasks and performing them better and faster than a worker trained on all stages of a house's construction. Faster and more efficient construction leads to lower costs per square feet. In the Northeast, onsite construction slows in the winter months; this slow-down can be avoided with a factory. During labor shortages, it is easier and more cost-effective to find and train individuals for specific tasks, rather than finding or training someone for all tasks, as seen in site-built construction.

The construction times for a modular home are usually shorter than for a site-built home, due to the efficiencies of line production, reduced set-up times, equipment organization, and ability to work through inclement weather. Unlike site-built construction where change orders are the norm, the design and construction process in a modular factory follows a strict process and timeline. Reducing change orders results in less waste, reduced material costs and avoiding costly time delays. In addition, as the module is being built in the factory concurrently with the job site being prepared, this also reduces the overall time of construction.

The quality that ZEM homes can achieve is also much higher than equivalent site-built construction. Houses need to be built well enough to be transported by carrier and lifted by cranes without damage. As a result, modular homes are typically stiffer and can often better able to withstand strong winds.[4] Factories that have invested in some degree of automation have more sophisticated equipment that can cut the material to very precise measurements. In the case of a turnkey package, the home can be finished in the factory, including air sealing, insulation, and testing of the envelope air-tightness (for single module homes).

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[3] For a more thorough discussion of the benefits of modular construction over stick-built, see: *The Modular Home*, Andrew Gianino, Storey Publishing, 2005

[4] FEMA, Building Performance: Hurricane Andrew in Florida. Observations, Recommendations, and Technical Guidance, February 1993. P. 29

To streamline the design process and logistics of line production, homes are often built to the most stringent building code that the factory delivers to, since differences in code vary by location. Also, a modular home can be more easily built to high levels of energy efficiency because the drywall is installed before the external sheathing and all the penetrations to the thermal envelope can be sealed from the outside (e.g. outlet boxes). In addition, modular home factories often require higher quality material from their suppliers. For common materials like lumber, the factory can send back low-quality material and request a replacement from the manufacturer. A one-off site constructed project is under more pressure to accept lower quality material that is delivered to the job site, to prevent delays. Finally, there is typically more quality control during construction than a site-built home, as factories often have a staff person dedicated to quality control.

**Modular Homes**

- Safe and comfortable space for worker, protected from weahter variability
- Better organized workplace
- Materials protected from sun and weather
- Overall lower costs when production process is streamlined
- Material can be bought in higher volume and lower cost, with off-season pricing in the winter
- Workforce can be specialize in fewer skills
- Quicker turn around time
- Less material waste
- Homeowner saves on construction loan and insurance

**Site-built Homes**

- Daily set-up and clean-up adds to construction time
- Crews spend more time moving equipement and material
- Vulnerable to weather events and vandalism during construction
- Custom build can mean higher costs for materials and labor
- Crews must typically have a comprehensive skillset
- Construction times are longer
- More waste in the construction stream

Because modular construction has different processes and timelines than site built, ZEM partners such as affordable housing developers and mortgage lenders must be willing to modify existing internal processes and re-train staff to ensure projects can harness the cost reduction benefits. This is an important consideration for ZEM pilot partners.

A more thorough discussion of the benefits of modular construction can be found in Volume 1: Market Analysis for Zero Energy Modular Homes in New York State.[5]

## Zero Energy Homes for Low Income Affordable Housing

Affordable housing developers face staggering challenges. Rising construction costs, labor shortages, hurdles with land acquisition and fluctuating federal and state grant and capital pools add to the

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[5] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

difficulties facing affordable housing developers. First cost and minimum code compliance often dominate their decision-making priorities.

What is unique about this concept is that ZEM factories will sell directly to affordable housing developers. Many standard modular factories engage with dealers who then work with clients. The dealer interface can increase the costs of the home. The ZEM Initiative will include a front office sales function that provides education and life cycle cost calculations that help affordable housing developers and prospective homeowners understand the total cost of ownership. A ZEM sales team or affordable housing provider can explain to prospective homeowners how zero energy homes reduce or eliminates energy costs, and how the quality and durability of the home reduce maintenance costs.

ZEM homes are all-electric, healthy homes built to the highest level of efficiency. A roof or ground mounted solar PV system is designed to produce as much energy as is used annually, and zero energy construction reduces the risk of energy cost volatility for residents because energy cost will be fixed for the life of the solar PV panels. They can also include grid-connected batteries. In partnership with local utilities looking to manage their peak loads, ZEM homes can be part of a grid modernization and battery storage effort.

Like many states, New York struggles with an increasing demand for, and inadequate supply of, affordable housing both for rental and homeownership. ZEM Factories build for two affordable housing types:  low to moderate income single-family homeownership or rental units, and mobile and manufactured housing replacements

ZEM homes designated for single family units must meet specifications of a developer such as aesthetics and size. Zero energy homes cost more than a baseline minimum code compliant home upfront (5-10% more)[6] but will save over the long term. ZEM factories will coordinate with affordable housing developers to access local energy efficiency and renewable energy programs that will help buy down the first cost of the home.

ZEM homes provide a unique solution to those living in mobile or manufactured housing communities who would like to purchase a new zero energy home. Manufactured housing, also factory built, is regulated by the federal government through the Manufactured Home Construction and Safety Standards, commonly referred to as the HUD Code, which was last updated in 1994. At this point in time, manufactured homes built to meet a stringent zero energy standard are not offered for sale to homeowners. A ZEM home sized to fit on the footprint of a MMH reduces energy burden for low- and moderate-income (LMI) households, adds high quality housing stock quickly, and provides a truly affordable alternative to traditional MMH, which are often energy inefficient and can be expensive to own as a result.

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[6] Alisa Petersen, Michael Gartman, And Jacob Corvidae, The Economics of Zero-Energy Homes Single-Family Insights, Updated 2019 With Cold Climates Addendum, Rocky Mountain Institute

## Market Assessment and Industry Characteristics

The findings from Volume 1: Market Analysis for Zero Energy Modular Homes in New York State[7] confirms that there is significant interest in and potential market demand for ZEM as an alternative to manufactured housing and single-family homeownership or rental. In Volume 1, the demand for ZEM homes is estimated at 10,000 homes over the course of a decade, but the limited capacity for building ZEM homes is the most significant barrier to advancing this housing solution.

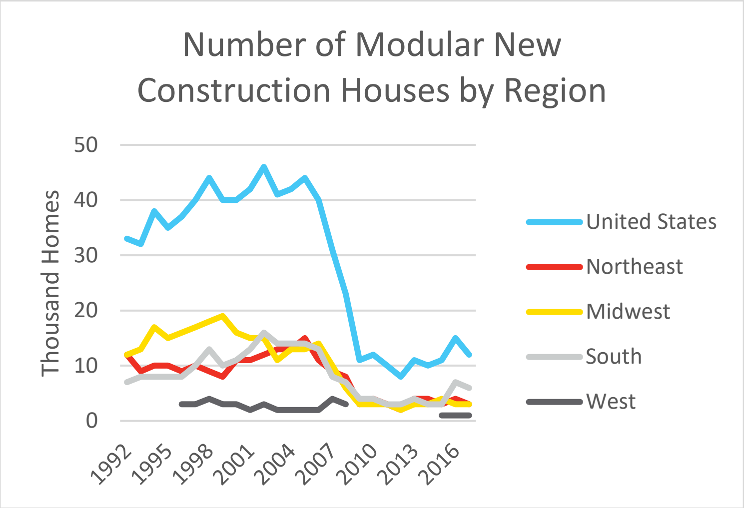

**Figure 1: Modular home construction trends.**

Prior to 2007, 39,000 modular homes were built each year nationally, including 11,000 in the Northeast. Following the downturn of the economy in 2008, this number declined to 12,000 nationally, including 4,000 in the Northeast (Figure 2).[8]

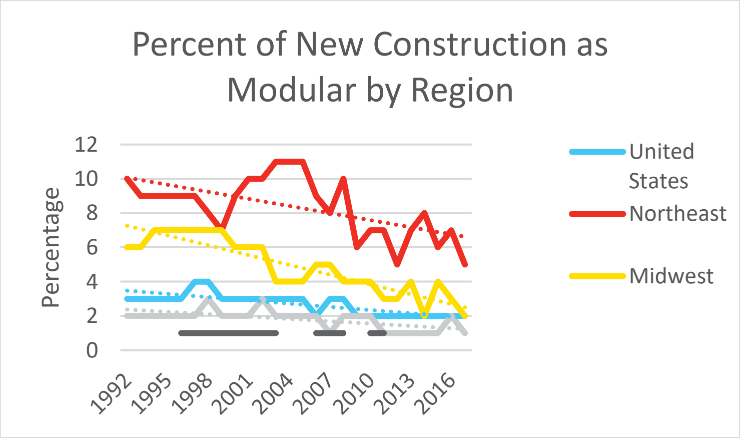

**Figure 2: Percentage of modular construction by region.**

While most of that decline was due to an overall decline in the number of new homes built, the share of the new construction market occupied by modular construction has also declined in every region of the country, and although the Northeast remains at the top of the list for percentage of new modular homes built, the historical decline is apparent.[9]

Currently, a dozen modular factories deliver homes to NYS, with a few incorporating energy efficiency and renewable energy as part of their business model. Depending on factory size and deliver capacity, between 5-10 additional ZEM factories will need to come online to meet the estimated demand over the next decade. Due to the current state of the market, it will take financial and regulatory support to further develop ZEM factory capacity to meet the demand projected over the next decades.

> Between 5-10 additional ZEM factories will need to come online to meet the estimated demand over the next decade. Due to the current state of the market, it will take financial and regulatory support to further develop ZEM factory capacity.

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[7] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state
[8] Census data, Type of Construction Method of New Single-Family Houses Completed
[9] Census data, Type of Construction Method of New Single-Family Houses Completed

# Zero Energy Modular Construction Process

## Characteristics of ZEM Homes

Zero energy modular homes are modular homes that are designed and built to meet a zero-energy standard. ZEM homes, like standard modular homes, are constructed in a factory in “modules” that are transported on a trailer to the site where they are placed on a permanent foundation by a crane. For homes built with multiple boxes, the boxes are joined together, and exterior finishes are completed on site. The modules must conform to size limitations when traveling on the road, determined by federal, state and local transportation regulations for height, length and width. See Appendix V for more information on specific sizes and restrictions.

To achieve zero energy, a ZEM home design goes through a design process to first reduce energy demand, then size a solar PV system to generate the energy used on an annual basis.

Generally, to ensure air tightness and efficiency performance, ZEM homes should preferably be fully finished in the factory, including all interior and exterior finish work and HVAC. Garages are also usually built on-site because the floor is concrete as opposed to wood and that doesn’t lend itself to modular construction.

A ZEM home built for a climate in the Northeast would be built to meet a prescriptive envelop standard, such as the one provided as an example in Table 1.[10] This standard can be achieved through a number of construction practices listed in Appendix V. However, the building design and energy modeling will determine the exact envelope and mechanical characteristics of the home. This in turn determines whether individual home designs can be considered zero energy or meet specific certification requirements. Pictures are provided in the section ZEM Construction Tasks and Process Flow that will help better understand design details.

> The building design and energy modeling will ascertain the exact characteristics. This in turn determines whether individual home designs can be considered zero energy or meet specific certification requirements.

**Table 1: Example of building characteristics of an existing ZEM home, in northeast climate zones 6.**

| **Envelope** | |
|---|---|
| Floor | R-40 |
| Walls | R-42 |
| Windows | U-0.21 |
| Doors | R-5 |
| Ceiling | R-60 |
| Infiltration | 1.0 ACH50 |

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[10] The following resource can help define prescriptive envelope standards in other climate zones: https://buildingscience.com/sites/default/files/migrate/pdf/BA-1005_High%20R-Value_Walls_Case_Study.pdf

| **Mechanicals** | |
|---|---|
| Heating | 13.5 HSPF |
| Cooling | 30.5 SEER |
| Hot Water | 2.75 EF |
| Duct Insulation | n/a because ducts are in the conditioned space |
| Duct Leakage | n/a because ducts are in the conditioned space |
| Ventilation | Balanced, 50 cfm, 62w |
| **Lights & Appliances** | |
| Efficient Lighting | 100% LED |
| Appliances | ENERGY STAR+ |
| **Photovoltaic System (PV)**[11] | |
| Climate Zone 4 | 5 kW |
| Climate Zone 5 | 6 kW |
| Climate Zone 6 | 7.5 kW |

Homes can be designed with lower R-values, as long as they have extremely low air leakage and negligible thermal bridging; however, this will require a larger PV system. The exact design should be cost optimized to find the right balance of insulation vs. solar PV production, especially as solar PV costs continue to decline.

ZEM home design model utilizes construction principles that result in comfortable homes, with excellent indoor air quality, durability, and low energy use:

- Continuous insulation throughout the entire envelope without any thermal bridging;
- Extremely airtight building envelope, preventing infiltration of outside air and loss of conditioned air;
- High-performance windows (double or triple-paned windows depending on climate and building type) and exterior doors;
- Solar gain managed to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season;
- Balanced heat- and moisture-recovery ventilation; and
- Minimally sized space conditioning system.

By utilizing high performance building principles, balanced ventilation with heat recovery, high-efficiency, all-electric HVAC, and ENERGY STAR lights and appliances, the energy demand and heating and cooling loads of a home are significantly reduced. After the efficiency is maximized, the solar electric PV system is designed to produce as much energy as the home uses on an annual basis. ZEM homes apply this principle while integrating strategies to keep the homes affordable and accessible to income-qualified buyers and renters. Strategies that can be used to keep costs low include lean manufacturing, just-in-time (JIT) deliveries, minimal batches and shorter lead times, and flattening the supply chain. These strategies are discussed further later in the report.

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The finish that is accomplished before delivery depends on specific business models. Except for areas where modules are joined on-site, a ZEM Home should be fully finished in the factory including all interior and exterior finish work, HVAC, flooring, plumbing, electrical and appliances to ensure air tightness and expected efficiency performance.

## Foundation

There are three options for ZEM home foundations: crawlspace, piers, and full basements. Modular homes are usually not built on a concrete slab because access is required for all utilities (water, sewer, electrical) below the first floor, which is not possible with a slab. As with site-built homes and regardless of the foundation type, it is important to ensure that the quality of the foundation is high so that the high-quality ZEM home is not compromised by a lower quality foundation. The foundation should be frost-protected and have good drainage, to ensure the home will not shift seasonally, potentially resulting in cracks.

**Figure 3: ZEM home being installed on a crawl space.**

The foundation type will be dictated by regional variations and site-specific considerations. For modular homes with multiple modules, one critical detail is the location of columns to support the marriage wall.

Modular factories typically design the foundation to ensure it matches the home being built, and work with a local general contractor (GC) that is familiar with construction practices and foundation details for highly efficient homes. The GC will prepare the site and install the foundation. Manufacturers usually prefer to design the foundation, to ensure that it matches the house being manufactured in the factory, rather than have the GC design the foundation.

## First Floor System

The floor strategy for a ZEM home depends on whether the home is placed on an uninsulated and unconditioned space, such as a crawlspace or piers, or a properly insulated, conditioned, and ventilated space like a finished basement. Most ZEM homes will be installed on an uninsulated, unconditioned space to reduce cost. This means that the first floor will need to be fully insulated, air sealed, and weather-tight while in the factory to maintain the benefits of modular, energy efficient construction.

While single module ZEM can sometimes be installed without a crane, further reducing costs, many ZEM homes require a crane to lift the home off the trailer and place it on the foundation. Floor assemblies for ZEM homes are designed to sustain the additional stress associated with the delivery and crane set and are therefore built differently than both manufactured and site-built floors.

## Exterior Wall Assembly

ZEM homes can be a single module or multiple modules. For ZEM modules, standard construction is 2x6, 24 inches on center, resulting in less wood than 16 in on center, for example, and fewer potential thermal bridges from the studs.

The ZEM exterior wall assembly must be durable, have thermal bridge-free construction, be super-insulated, and air tight. To meet these stringent standards, factories can follow construction steps that prioritizes high performance building standards. For instance, factories can install gypsum wall board before exterior sheathing so all penetrations (e.g. electrical outlets) can be sealed from the outside before insulation is installed. Another approach that ensures air tightness involves installing all exterior wall gypsum wall board prior to setting interior walls or soffits, to ensure a continuous air barrier. These construction methods are not available when building on site, because with site-built construction, the priority is to finish exterior sheathing to protect the home from the weather.

Some modular factories take a hybrid approach, assembling a home using both modular walls and structural insulated panels (SIPs), which are built in a facility that specializes in a panelized wall construction. While SIPs are more expensive than many modular wall systems, this approach can be used to reduce factory labor requirements and the time required to build a house. However, one of the drawbacks is less flexibility for modifications (e.g. changing the location of switches). It can also be challenging to find a distributor for SIP panels, depending on the ZEM factory location. SIPs can be used as walls in modular zero energy construction[12] for affordable housing but they tend to be costlier. A factory would need to have sufficient production volume to be able to negotiate a reasonable price to use SIP walls in affordable housing production. Alternatively, SIPs could also be used only for very specific applications.

## Roofs

If a ZEM home roof is designed flat or slightly pitched to meet size limitations determined by transportation regulations for height, it should be finished (insulated, air and weather-tight) in the factory. If the home's design requires a steeper pitched roof, modular builders can integrate part of the roof system in the factory through a hinged roof system.

Sections that contain the roof can be more challenging if the roof has a steeper pitch built on-site, or as panel construction, rather than in modular factories. Porches and decks would cause the module to exceed the size limitation.

**Figure 4: Example of hinged roofs (Huntington Homes, Vermont).**

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[12] E g. modular homes built by https://www.solarhomefactory.com/tech and http://gomodularhomes.com/about-us/

In the MMH replacement scenario, ZEM homes incorporate a low pitch shed or gable roof system. As with other assemblies, the roof systems are designed to ensure a thermal bridge-free assembly, long term durability, super-insulation, and air tightness. Completing the roof system in the factory not only makes achieving these characteristics easier in a climate-controlled environment but also allows the factory to install the majority of the solar PV system, further reducing site work and the system's overall costs. The low pitch roof also allows the ZEM home to be sited without ideal solar orientation when compared to a home with a steeper pitched roof. The flatter roof assembly is similar to a commercial PV installation, where solar production is maximized in the spring, summer and fall with reduced production in the winter when the sun is lower in the southern sky and snow may accumulate on the modules.

**Figure 5: ZEM low-pitch roof in a MMH replacement project**

## Windows and Doors

For a ZEM home, windows and doors are specified to ensure comfort at the perimeter of the home without confining distributed heating and cooling to those locations. ZEM homes utilize highly insulated and highly airtight casement, awning, fixed-pane, and tilt-and-turn windows. Unlike single and double hung slider windows which rely on a tracking system and single gasket where sashes meet, ZEM windows rely on a multi-gasketed, compression closure system for a tight seal.

## HVAC and Hot Water

HVAC systems are very important in ensuring the house meets the zero energy goals. Not only is the choice of an appropriate HVAC system critical, but having it installed correctly is also a key to meeting the expected building performance. All components (e.g. vents, outdoor compressors, indoor units) must be located in an appropriate part of the house for the system to work most efficiently and for the heated or cooled air to be distributed evenly. Typical modular homes do not have the HVAC system installed in the factory, but rather rely on an HVAC technician to install the system on site after the house is delivered and set. The HVAC system in a ZEM home is finished in the factory, other than a few duct connections required in multiple-box homes. Commissioning is also performed on site after the HVAC system is fully installed. Every ZEM home should have all ducts located within the thermal envelope, ENERGY STAR certified equipment, and Water Sense fixtures to reduce water usage (including hot water).

### Solar PV

**Figure 6: Solar PV system on a flat roof.**

A PV system that is matched to the expected electric load of the home is typically installed with a ZEM home. It is generally better to reduce the electric load of the home first and size a smaller solar PV system, than install a larger than necessary solar PV system in a less efficient home, as this would be costlier and may not as beneficial to the electric grid.[13]

A modular home with a 2/12 roof pitch (12.5%) or less can be placed in most orientations due to the low slope without significantly impacting solar production. As the roof pitch increases, a solar PV system will be more impacted by its orientation and should be sited within 15 degrees of true south. Tools (e.g. the National Renewable Energy Lab (NREL) PV Watts tool) should be utilized to evaluate sites and design the system for a specific location. All of the PV system's wiring, inverters, and racking system can be installed in the plant prior to shipping. Once the home is set on site, the modules can be installed and connected, reducing the cost for installation compared to a typical site-built PV system.

For sites where solar PV is not optimized due to immovable shading, building configuration, or site orientation, a ZEM home should be installed without the rooftop solar component and off-site or community solar should be utilized to cover the house's energy usage. This would be necessary for the ZEM house to be considered zero energy, and may be required in the future for eligibility in zero energy incentive programs.

## ZEM Home Certifications

Zero energy means that over a year, the houses produces as much energy as it consumes, resulting in zero energy consumption, and negligible energy bills for the resident. One way to verify that a home meets the design criteria, is to have them certified by a national home labeling program. These certifications can usually be done by working with local companies that are accredited for each certification label.

Certifications can take place at the factory and home level and will require partnerships with RESNET Accredited Home Energy Rater. As part of the design process, ZEM homes should be designed to qualify for specific national building certifications. Certifying these homes provides several advantages:

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[13] E g. https://www.hiveforhousing.com/design/residential/did-we-get-zero-energy-wrong-arizona-builder-designs-for-the-grid-not-net-metering_o

1. Quality assurance that these homes will perform to the highest standard possible
2. Marketing recognition and support
3. Technical assistance and support

The certification process follows the following steps:

- The builder enrolls the project in a voluntary certification program
- A Rater is then assigned to the project

- The home design is reviewed by the rater

- Inspection and certification with a home energy model, which will in turn provide a Home Energy Rating (HERS) Index.

Participating ZEM factory builders will need to partner with HERS Rater(s) to provide a Rating Certificate for each home. An energy model takes the home technical specifications, dimensions, climate zone, and performance testing and generates estimated annual energy consumption. The results of the model are converted to a score or index. The lower the number, the less energy a home consumes compared to a similar home built to the minimum energy code. Zero energy buildings combine energy efficiency and renewable energy generation to consume only as much energy as can be produced onsite through renewable resources over a specified time period.

The following are certification programs a ZEM factory should consider:

- **US Department of Energy (DOE) Zero Energy Ready Homes (ZERH)** certification is given to homes that demonstrate exceptional energy efficiency performance. More information can be found here: https://www.energy.gov/eere/buildings/zero-energy-ready-home. To qualify under this program, the home must be designed to meet **ENERGY STAR** certification requirements. The home must also meet the full certification in **EPA's Indoor airPLUS** Program, a labeling program that helps achieve good indoor air quality.
- The **Passive House Institute U.S. (PHIUS)** offers a labeling program called **PHIUS+** that combines a thorough design verification protocol with a stringent quality control program done on site by PHIUS+ raters and verifiers. More information about the details of the standard can be found at http://www.phius.org/phius-2015-new-passive-building-standard-summary

## ZEM Construction Tasks and Process Flow

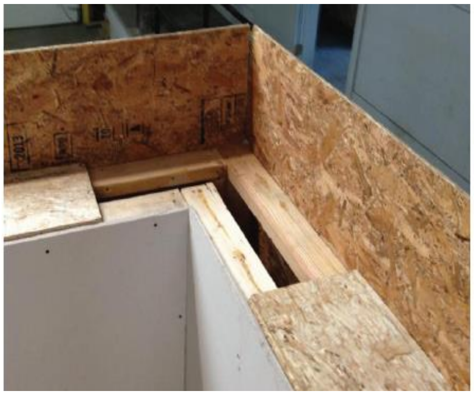
Table 2 below illustrates the critical steps required for constructing a ZEM home in the factory. An existing factory can modify their designs and production steps to integrate the characteristics of a ZEM homes into their processes. A new factory can use these critical steps described below to assist in the design of a production line specific to ZEM homes. It is essential that ZEM homes meet the designed air sealing requirements and all construction steps should aim toward that goal. For example, crews should understand that they are responsible for sealing any hole that they make in the building envelope.

The following steps and their order will vary depending on the construction strategy and house specifications used to achieve zero-energy, and whether the ZEM home is a turn-key mobile home replacement, or a more typical modular single-family home. The steps and description below assume the home is completed at the factory, including all interior and exterior finishes, HVAC, hot water system, flooring, lights and appliances, and fully painted. This is an example and in practice the steps may vary depending on home design and factory configuration.

The steps below assume that the floor will be insulated and made weather-tight at the factory (which is necessary with an unconditioned crawlspace or pier foundation). Insulating the floor at the factory takes advantage of the benefits of modular construction, compared to insulating, air sealing, and installing the weather barrier on site.

The tasks can be grouped into fewer stations or separated into additional stations. Some tasks could be pulled out of the production line into subassembly bays, if any activities slow down the flow of modules and creates bottlenecks. As a case study and example of how these steps could be set up, detailed installation steps used at the Vermod factory are provided in the Appendix IV.

**Table 2: ZEM construction tasks.**[14]

| Activities | Details |
|---|---|
| **Cut framing components (off-line)** | • Cut framing components for<br>○ Floor<br>○ All walls<br>○ Roof, fascia, and soffit |
| **Assemble floor and walls** | • Subassemblies (off-line):<br>○ Build Floor<br>○ Build exterior walls with window/door opening subassemblies (on deck, Figure 8):<br>• side walls<br>• end walls<br>• marriage wall (if house is comprised of more than one module)<br>○ Assemble partition walls, not on deck, to be erected later<br><br>**Figure 7: Upper section of sheathing running one foot past the top of the wall.**<br>• Install exterior top sheathing on exterior walls: if the roof is built using SIP panels, they will need to rest on a structure connecting them to the walls. One strategy to achieve that is to install the top part of the sheathing (1/2' OSB for example), so that a foot of it sticks out higher than the wall, to connect the air and weather barriers (Figure 7). The sheathing can be installed Figure 8 on the exterior walls before they are set, for ease of installation. |

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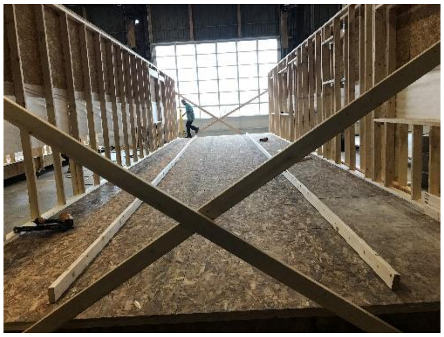
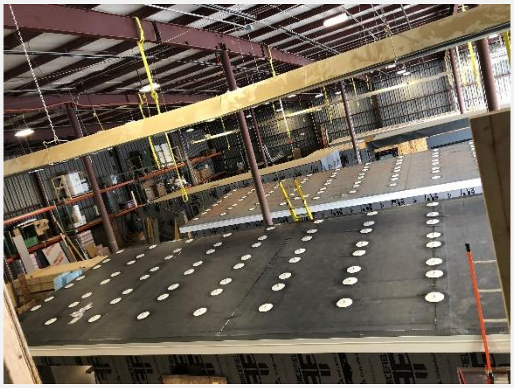
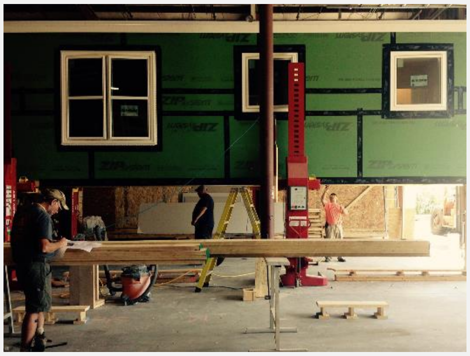
[14] All photos are from Vermod, Vermont

| Activities | Details |
|---|---|
| | • Erect and install walls on floor (Figure 9)<br><br>**Figure 9: Double walls raised onto the floor.**<br><br>**Figure 8: Exterior walls being built on deck.** |
| **Assemble and set roof** | • Subassemblies:<br>  ○ Build subassemblies for roof<br>  ○ Build roof/ceiling<br>• Install roof onto walls (e.g. Figure 10 with SIP panels)<br><br>**Figure 10: Crane lifting roof onto walls.** |
| **Drywall and rough-ins** | • Best practice construction to achieve a very tight building envelope is to sheath, tape, and mud all the exterior walls (and ceiling if applicable, Figure 11) to act as an air barrier prior to building the interior walls, soffits, and HVAC rough-in. ***This is different from how most modular factories operate.*** Depending on the factory layout and crew workflows, this might not be practical or might add a bottleneck. A tight building envelope can still be achieved by installing interior partitions before the drywall, and using an<br><br>**Figure 12: Installation of HVAC soffit and interior partitions.**<br><br>**Figure 11: Drywall installed on all exterior walls and ceiling.** |

| Activities | Details |
|---|---|
| | alternative air barrier approach, but this may add time, costs, and labor to the construction. If drywall is installed on ceiling prior to the partitions and rough-ins, the roof may need to be installed prior to this as well (see next bullet point). Drywall is typically glued to the studs, then screwed.<br>• Install interior partition walls.<br>• Installing the soffit for the HVAC ductwork on top of pre-installed drywall (Figure 12) is best practice but will require framers to come back down the production line and will need to be factored in the production workflow. The HVAC installers can do the soffits and the ductwork as one phase of work.<br>• Install rough electrical in walls.<br>• Air seal/ spray foam all penetrations (e.g. around electric boxes) from the exterior of the home. It is not necessary to spray foam every stud bay, especially if the drywall was glued to the studs.<br>• Build plumbing subassemblies.<br>• Install rough plumbing in wall.<br>• Rough in mechanical/ ducts. |
| **Drywall interior partitions and paint** | • Hang drywall on interior/partition walls<br>• Tape, mud, and sand drywall<br>• Prime and paint all walls and ceiling |
| **Sheath and insulate roof** | • Can be done simultaneously with interior drywall and rough-in installations<br>• Install rough electrical and plumbing in roof (if applicable)<br>• Sheath and insulate roof (if applicable) |
| **Prep/ drop roof (if applicable)** | • Shingle roof or install rubber membrane for flat roofs (if applicable)<br>• Install fascia and soffit (Figure 15)<br>• Install anchors for the PV racks, and racks (Figure 13). On pitches less than 4/12 the building code often does not allow for shingles on the roof. In that case, a rubber membrane can be installed in the factory and anchors for the PV racks can be installed. These consist of special adhesive-backed fasteners. The PV modules are typically installed on site to avoid damage during transportation. On steeper roofs, roof trusses can be delivered to the site and the PV racks installed on site.<br><br>**Figure 13: PV anchors installed on rubber membrane.** |
| **Prep walls, set windows,** | • Install finish electrical<br>• Insulate exterior walls, from the outside (Figure 14)<br>• Sheath walls, tape all seams and rough openings (Figure 15) |

| Activities | Details |
|---|---|
| **exterior finish** | • Install windows and exterior doors<br>• Install siding and exterior trim<br><br>**Figure 15: All seams taped, fascia being installed.**<br><br>**Figure 14: Insulation with dense pack cellulose, top and bottom sheathing already installed.** |
| **Interior finishes** | • Interior finish: paint trim and doors off line and then touch up after installation<br>• Install interior doors<br>• Install flooring<br>• Install interior trims and touch up as needed<br>• Install cabinets and counter tops<br>• Install appliances<br>• Exterior door casings<br>• Install closet shelves and doors<br>• Finish interior painting<br>• Install door hardware<br>• Install finishing plumbing, fixtures, bath hardware and accessories |
| **Finish electrical, and mechanical** | • Install HRV or ERV (if applicable, Figure 16)<br>• Install heat pump (if applicable, Figure 17)<br>• Install Water heater |

| Activities | Details |
|---|---|
|  | • Install light fixtures<br>• Install panel trim<br><br>**Figure 17: Compressor for heat pump installed on brackets on the outside of the house.**<br><br>**Figure 16: CERV and heat pump water heater in mechanical closet.** |
| **Finish plumbing and floor** | • Jack-up house with hydraulic lift or move to sunken floor<br>• Install plumbing in floor (if applicable)<br><br>**Figure 18: ZEM home jacked-up on hydraulic lift.**<br><br>**Figure 19: Insulation, and partially installed sheathing.**<br>• Insulate and sheath floor. If the building is going to be delivered as a finished product ready to set on a foundation or piers, the floor will need to be insulated in the factory. |

| Activities | Details |
|---|---|
| **Load shiploose, pack and ship** | • Clean Modules<br>• Test systems<br>• Final inspection<br>• Build, load, and strap shiploose material<br>• Strap refrigerator and other appliances as necessary<br>• Load on carrier |

## Site Work, Delivery, Setting, and Finishing

Ideally the factory would not only build the modules in the factory, but also transport, set and finish the modules, and do the site work, to ensure the quality is maintained in all components of the house and throughout the process. This will not always be feasible depending on the location of the home and the factory's business model. The factory may perform only some of the tasks outside the factory, in which case the responsibility for the house will be transferred at various points. The site work begins before the module leaves the factory and is the responsibility of the GC throughout the construction process. After leaving the factory, liability and responsibility for the modules transfer over from one party to the next as illustrated in Figure 20 below

During assembly in the factory, the modules are the responsibility of the factory, and liability resides with the factory. Once the module is lifted onto the truck, it becomes the responsibility of the trucking company. Another transfer of liability takes place once the crane lifts the module to set in onto the foundation, when it becomes the responsibility of the set crew. The general contractor (GC) will become responsible for the house following a walkthrough of the building with the set crew. The general contractor will retain liability on the house until the final walkthrough and handout to the customer.

If any defect or quality issues is found at the transfer points or while the house is under the responsibility of one of the parties, the party responsible will be charged with fixing the problem.

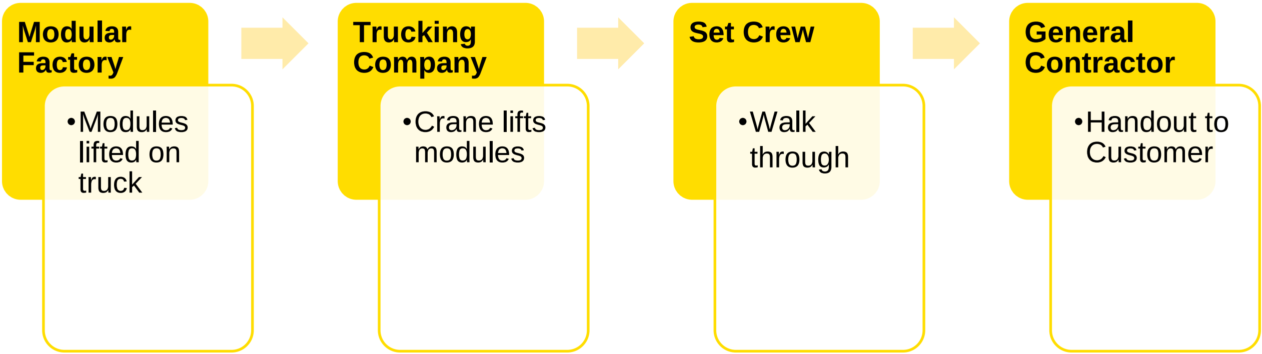


**Figure 20: Liability and responsibility from construction to final handout to customer. The factory may perform some or all of these tasks.**

**Figure 21: Setting of a ZEM MMH replacement onto its foundation.**

It is essential that the set crew and GC are vetted by the ZEM factory, to ensure they have been trained to work on ZEM homes, have experience setting and finishing modular homes (including joining multiple boxes) to ensure structural, air tightness, and insulation requirements are maintained. The GC should understand key characteristics of a ZEM home and avoid potential pitfalls when setting and finishing a ZEM home. This is vital to ensure that the ZEM home performs as expected and conforms to all building code, voluntary energy standards, and third-party certification inspections before being handed over to the customer.

For multiple-module homes, the modules will need to be joined on site. To maintain the air tightness of the homes, two common methods are used to join modules:

- A rubber gasket located between the two modules to be joined;
- Planning for a small gap between the studs and joists where the modules will be joined and filling that space with spray foam.

In both cases the exterior sheathing will also need to be taped on all walls, roof, and underside of the house, when applicable. Joining the modules also involves finishing the flooring, exterior siding, and drywall where the modules are connected, as well as connecting the following systems between the modules:

- Electrical
- Ducts (e.g. ventilation ducts)
- Hydronic (if applicable)
- Plumbing

It is important that the same quality is maintained when joining the modules and finishing the home on site, as what was constructed in the factory. The set crew must understand the quality standard for the ZEM home and strive to meet it. Once the modules have been joined, a blower door test can be performed and any additional air sealing necessary to meet the ZEM standard and third-party certification can be done then.

## ZEM Home Building Timeline

Compared to a traditional code-level home, a number of ZEM-specific characteristics will add time to the building timeline, such as air sealing, super-insulation, triple-glazed windows, balanced ventilation, and preparing the building for the solar PV system.

In addition, the time necessary to complete a home in the factory will depend on several factors:

- The comprehensiveness of finish of the module, i.e. what components are built and incorporated in the factory or installed on site after the modules are set. For example, flooring, HVAC, cabinets, etc. could be factory-installed or installed on-site.
- The number of modules per home and whether the factory is large enough to work on those modules in parallel, or whether the production must be staggered and modules stored at the factory site until delivery. Multiple modules also will require additional setting time to tie the modules.
- The complexity of the design and degree of customization available. One-off, custom homes take more time to build than designs that are repeated over many homes with few modifications.
- The complexity of the wall, floor, and roof assemblies. Highly insulated and tight building assemblies take longer to build because a lot of attention needs to be paid to the details, such as sealing all the wall penetrations, or integrating adjacent assemblies such as connecting the air barrier between assemblies.
- The factory layout. Line production saves time because materials can be stored next to the station where they will be used. Line crews are trained to perform only the tasks at a specific station and can do those tasks efficiently. Bay or crib construction can take longer because crews are generally able to do all the construction steps but may do each task less efficiently. The staging of material in crib construction cannot happen right next to the module being constructed and therefore requires more crew and material movement, which adds to the production time. Generally, more compact factories require less crew motion and less material transportation time than elongated factories, shortening the production cycle.
- The degree of automation. Machines can perform tasks such as picking up the lumber from a specific pile, cutting the lumber into the appropriate size and shape, nailing an assembly, dense packing insulation to the right density, sheathing, etc. at great speed. This can increase the production rate but at a higher upfront investment cost.

Given the factors above, production can vary from roughly 12 working days per home or less, to 45 working days or more per home. An hourly breakout is provided in Appendix VII as an estimate, underlining the fact that the time necessary for each step will vary depending on:

- The specific home design
- The strategy used to achieve zero energy
- The factory layout
- The efficiency of the construction process
- The crew’s skills and productivity

Setting the home and finishing it on site can take a matter of days if all the systems have already been installed in factory, or 2 weeks to several months if additional work is required after setting the module(s) on the foundation. Individual tasks will require a variable amount of time, depending on the factors listed above. ZEM homes are a new concept and therefore, existing ZEM factories are currently small and do not take advantage of automation improvements. To learn more about the expected timeline with various factors, see Appendix VI.

# ZEM Factory Business Plan Toolkit

## Factory Size

For efficiency of production, this guidebook recommends that the ZEM factory exclusively produces ZEM homes and sells directly to customers or affordable housing providers. It will be easier for a factory to consistently meet the demanding zero energy requirements of a ZEM home is the staff builds exclusively to this standard. Existing factories that wish to exclusively produce ZEM homes may need to take some steps to adjust their production lines and sales plan, such as:

- Building new relationship with suppliers of material appropriate for ZEM production
- Working with existing modular home dealer relationships and affordable housing providers to agree on a few zero energy standard designs that allow for some customer customization, and mass produce those designs at a low cost
- Vetting existing facilities and operations against the requirements for a ZEM factory, including stations, equipment, labor, operations and equipment (see Appendix I)

The remainder of this section is focused on a new factory start-up.

Most modular and panelized homes factories in the Northeast used an existing building (e.g. warehouse or old plant) rather than building a new one. Supply of underutilized industrial buildings of the appropriate size does not seem to be a major barrier currently. The minimum building and lot requirements and staffing requirements for the factory will be based on planned production.

In Table 3, the size expected for a start-up factory are highlighted in the gray box. If market conditions were appropriate or demand was significant, for example pilot programs that create demand for ZEM homes, then a greater production volume and factory size may be achievable even for a start-up. The factory size and labor hours necessary to complete the work will vary depending on the complexity of the home built. A highly insulated, thermal-bridge-free and air tight house design will require more time to complete than a typical code-compliant modular home. A lean and highly efficient factory with a stable and well-trained workforce will likley be able to achieve a greater volume of production with lower labor hours and fewer employees than the conceptual averages presented in the table.

Variability on production rate and labor hours will also be a result of work content linked to module design and specifications. Some factories might finish some work onsite (e.g. HVAC), or have different levels of completion (e.g. turned key, or 80% completed), or customization levels including energy efficiency techniques/materials. The values in Table 3 assume a turnkey package including HVAC.

**Table 3: Conceptual factory size and required workforce for a number of production scenarios, assuming one work shift.**

| Approx. Module per year | Approx. Plant Floorspace (sq. ft) | Approx. Labor Hours per Module | Approx. Labor hours Annually | Approx. FTE, Direct Production |
|---|---|---|---|---|
| **50** | **10-20,000** | **440-1,200** | **24,000** | **20** |
| **70** | **20,000** | 450 | 31,500 | 20 |
| **160** | **45,000** | 400 | 64,000 | 30 |
| 260 | 70,000 | 350 | 56,000 | 30 |
| 350 | 95,000 | 350 | 91,000 | 50 |
| 440 | 120,000 | 350 | 122,500 | 60 |
| 530 | 145,000 | 350 | 154,000 | 80 |
| 620 | 170,000 | 350 | 185,500 | 100 |
| 720 | 195,000 | 350 | 217,000 | 110 |

## Factory Location and Layout

Ideally, for homes shipped beyond the local market, a factory should be located within a short drive (15 minutes) of a major highway, to reduce transportation time and costs. Other considerations include the availability of incentives for brownfield development and availability of redevelopment funds. Regional development agencies are usually available to assist in site selection based on economic development incentives and New Market Tax credit (NMTC) available. Examples of subsidies offered in New York State are provided in a section below.

**Figure 22: Rollers.**

A start-up can secure a portion of the building and share it with other industries. As the business increases, the modular factory may have the option to occupy a larger part of the building. Factories should have column spacing and height clearances that are compatible with the factory layout. The warehouse, where materials are stored, can be attached or be delineated space within the factory. Incorporating staging within the factory is generally more efficient than in a separate warehouse. Generally, about 70% of the factory's square footage should be dedicated to the production line, and 30% to receiving, staging, and shipping.

To determine the factory size and layout of a factory relying on line production, one should:

- Work from the ZEM module specifications to determine the amount of work;
- Identify activities common to all modular construction and those specific to a ZEM home;
- Use published times for common activities and case studies for special ZEM activities;
    - Calculate the optimal number of workstations and layout to achieve the most efficient layout.

A number of layouts are possible for setting up a factory. The plan will depend on whether the units are built in place (Figure 24: Crib or Bay construction), whether they are built in a set production line and moved along fixed rollers (Figure 22) or rails, or whether they are on air pads (Figure 27) or casters attached to the modules, and moved along a more or less set flow. Tracks are generally not a recommended choice because debris tend to accumulate in the tracks and cause problems. Casters and air pads are the most flexible options for moving modules around the factory floor, with air pads being more expensive. Flexibility in moving the modules is helpful if a module needs to be temporary pulled off the production line, or if the factory expands or contracts with fluctuating demand and the layout of the factory line needs to be changed to accommodate for the change in demand. The following figures illustrate the various layout options. If the factory has a sunken floor to allow for work on the underside of the first floor (as opposed to using jacks), then this will place constraints on the layout options for the factory.

**Figure 27: Air pads.**

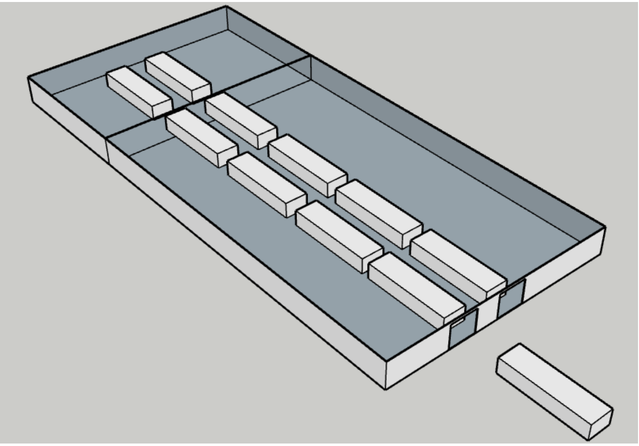


**Figure 26: Shotgun line layout.**

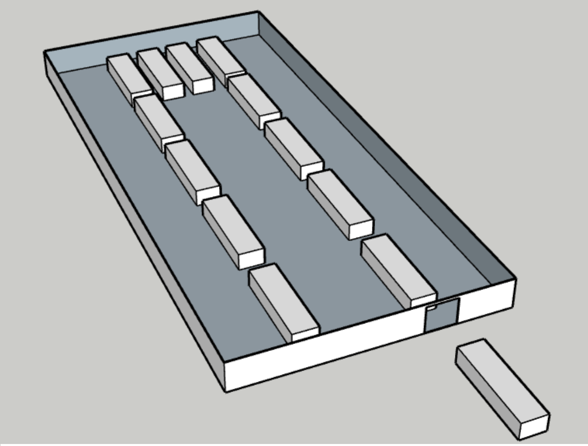


**Figure 25: Horseshoe line layout.**

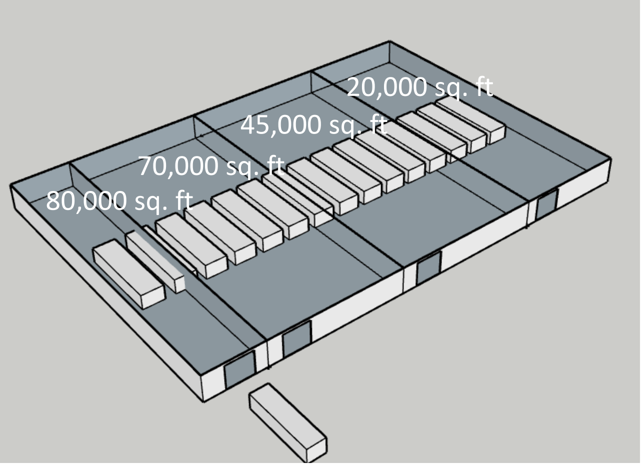


**Figure 23: Sidesaddle line layout.**

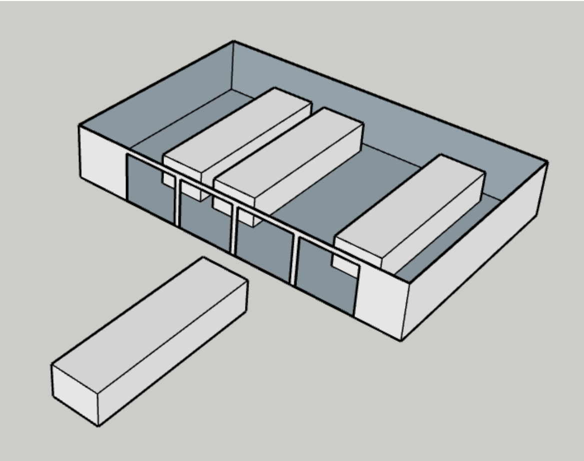


**Figure 24: Crib or Bay construction.**

**"Crib", or "Bay" construction** (Figure 24) works well for a start-up because it requires less equipment and does not require material handling equipment (e.g. cranes) and extra space to move the modules other than loading them on the carrier upon completion. Crib construction also works well if each module is highly customized or if the volume of production is relatively low. While a ZEM factory should strive for standardization of modules to keep costs low, if needed crib construction can also be set up so small modules can be moved around the space on casters, and laid out as they would be set, for complicated custom designs. However, crib construction has limited capacity to expand, without a major investment into an additional building space.

If the volume of production is higher, a line production can allow for shorter production time, and a relatively lower cost per module, with more specialized crews at each station. The shotgun line layout (Figure 26) is often used for line production. It can be modified into a T, an L, or a horseshoe shape (e.g. Figure 25), depending on factory layout and volume of production**.** A sidesaddle layout (Figure 23) may be preferred depending on building layout and construction processes.

**Table 4: Summary of pros and cons of different plant layouts.**

| Plant Layout | Pros | Cons |
|---|---|---|
| **Crib or Bay** | • Well-suited for a start-up<br>• Requires less equipment<br>• Does not require equipment and space to move the modules other than loading them on the carrier upon completion<br>• Suitable to more customized modules | • Limited capacity for expansion<br>• Doesn't benefit from line production efficiencies<br>• Required cross-trained workforce<br>• Required higher levels or workforce coordination |
| **Side saddle, (straight or L-Shaped)** | Compared to a shotgun layout:<br>• Because of the module orientation, the facility does not need to be quite as long, and can be more compact<br>• It is easier to build catwalks in a more compact building<br>  • Material does not need to be moved far in a compact building | Compared to a shotgun layout:<br>• Access to the interior of the module (for homes with multiple modules) is only through the marriage wall and if that is against another module, access is more difficult. |
| **Shotgun layout (straight, L or U-Shaped)** | Compared to a side saddle layout:<br>• Better access to the interior through the marriage wall, a forklift can drop sheetrock directly into the module if it is in a shotgun position, it cannot in a sidesaddle. | Compared to a side saddle layout:<br>• Long facility may be required, resulting in material and people needing to move further, taking more time. |

Whether the construction line is sidesaddle or shotgun, the number of workstations and amount of work done at each workstation can vary, to adapt to the facility size and layout. If space allows, a module can be pulled out of the construction line to customize or add additional features that would create a bottleneck if the module stayed in the line. From an efficiency standpoint, factories should construct mostly standard modules, with customization allowed as tiers or packages, as excessive customization reduces production efficiency.

The number of stations in the construction line are determined by starting with two basic models that the factory is expecting to produce, determining the steps to construct those modules, and then consolidating the steps to fit the factory plan. With line production, if demand increases, the number of stations can be consolidated, and more work done at each station, to allow for higher volume production. For a 20-40,000 sq. ft factory, an example would be to have two sidesaddles with bay station pull-outs for customization or floor construction. This would allow the production to take place in a compact facility.

If the production line starts as a linear sidesaddle, and if space allows, the production line can be modified to L-shaped, or U-shaped for increased production (e.g. Figure 25). Similarly, a shotgun production could be modified to a sidesaddle production line to increase the number of stations and scale up production.

Access to the factory from more than one side is preferable, to allow material delivery close to where it is stored. Oversized garage doors (e.g. 18’x20’) will be required where completed modules exit the factory. Outside the building, there needs to be another 100 feet of pavement for truck movement, and some storage area for completed modular boxes that cannot be shipped on the day they are completed for unforeseen reasons. Factories typically strive to ship the modules upon completion to avoid needing to store the completed modules on site and risk damage to the modules.

## Factory Set-Up Costs

A detailed list of equipment needed for a modular factory is provided in Appendix II and summarized by category in Table 5 below. The tools necessary for a modular home factory will be highly dependent on the level of automation and manufacturing processes - which will in turn be dependent on the volume produced. High-automation levels only warrant the investment if the volume of production is high. On a small volume of homes, the investment in sophisticated machines will likely never be recovered.

Start-up factories will need to acquire fewer tools if they hire subcontractors for specific, specialized tasks. One way for a start-up to minimize risks in the initial stages of production is to lease or rent space and equipment instead of buying them immediately. Alternatively, the factory could purchase second-hand equipment, for example from other modular home factories that have upgraded their equipment or went out of business. These approaches also work for established factories that are adding ZEM to their product line.

Start-up factories can increase the level of sophistication of the assembly lines as the production volume increases. Smaller factories and factories with fewer employees will see lower tool costs; larger, more automated factories will see higher tool costs, but often fewer labor hours per module.

Tools will also depend on what components of the house are built in the factory and what components are installed after the house is set. For example, if the floor system is fully insulated, air sealed and made weather-tight at the factory, the factory may have hydraulic lifts to elevate the home to fully detail the underside of the home. If the floor is left uninsulated, hydraulic lifts may not be needed.

In the table below, we assumed a start-up factory (rather than expanding production to ZEM homes in an existing modular factory) moved into an existing warehouse that was not previously utilized as a modular home factory. Therefore, we are assuming costs such as wiring the building and setting up compressed air at each station are necessary. These costs will vary depending on the actual building. We included costs for a larger factory are included as well, for comparison purposes and in the cases where a factory developer has access to a large amount of capital and is interested in lowering per module costs through higher volume production.

*The costs presented below are approximative and conceptual, to provide a general range of costs. Actual costs may vary.* Costs and number of units required are based on literature review and professional judgment. Costs will vary greatly depending on whether the factory owns delivery trucks or hires as needed. More details costs are provided in Table 5, to assist in designing budgets and business plans for specific situation. The costs presented below assume all new equipment, costs could be reduced by up to 40% by acquiring used equipment from idle or closing plants. Equipment costs will also vary regionally.

**Table 5: Conceptual new equipment and start-up costs by factory type**

| | **Small, crib-build factory**<br>• **20-40,000 sq. ft**<br>• **50-70 modules/yr** | **Small, line production, low-automation factory**<br>• **20-45,000 sq. ft**<br>• **70-160 modules/yr** | **Larger, Higher Automation Factory**<br>• **70-100,000 sq. ft**<br>• **250-360 modules/yr** |
|---|---|---|---|
| **Equipment Costs Subtotal (See Appendix II)** | **$452,000** | **$793,800** | **$1,400,000** |
| **Wiring** | $30,000 | $135,000 | $300,000 |
| **20’x18’ garage doors**[15] | $32,000 | $16,000 | $16,000 |
| **Plumb building for central compressor** | $3,000 | $13,500 | $30,000 |
| **Construct paint booth** | $10,000 | $10,000 | $20,000 |
| **Office furniture** | $500 | $1,200 | $1,500 |
| **Computer systems (hardware, software)** | $10,000 | $45,000 | $100,000 |
| **Building Set-up Subtotal** | **$135,450** | **$445,700** | **$967,500** |
| **Prototype home cost** | $150,000 | $150,000 | $150,000 |
| **Total** | **$737,450** | **$1,389,500** | **$2,521,500** |

Building operational costs (lease, electricity, heating, water) will vary depending on building characteristics. Adequate ventilation is needed to meet OSHA regulations, and while in the summer it can be done by opening doors and using fans, ventilating the building in the winter will impact heating costs. The right ventilation can prevent air quality problems. Although OSHA does not have indoor air quality standards for modular factories, it does have standards about ventilation and standards on some of the air contaminants that can be involved in indoor air quality problems. Areas exposed to more fumes and droplets, such as painting stations, may require additional ventilation, in addition to the use of personal protection accessories. While using spray foam  to insulate wall cavities is not recommended due to air quality concerns, if the factory decides to use this method, it may require additional ventilation requirements, in addition to general factory ventilation.

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[15] Note: crib factories require more large garage doors than line production, because one door is associated with each bay.

Understanding capital costs and operating costs will be important for the factory developer to understand the return on investment. For example, assuming a ZEM home can be built for $130 per square foot, and sold for $150 per square foot, or $150,000 for a 1,000 sq. ft home, then the margin will be $20,000 per home. Assuming a small crib factory building 50-70 homes per year, then $1-1.4 million will be available to cover costs and reinvested in the factory and its employees. Assuming a highly efficient line production can cut construction costs by 25% compared to crib construction, then the margin per home would become $60,000 (production cost of $90 /sq. ft, assuming the home retail price remains the same) and may justify the investment in line production and automation. Therefore, the return on investment will be highly variable depending on factory type and layout, operating costs, and production volume.

## Labor Requirements

The cost structure for a typical modular producer is:

- Materials: 45-50%,
- Overhead 35-45%, and
- Labor 10-20%.[16]

Direct labor requirements will vary depending on the production volume. For a production of one to two modules per day (a 20,000-45,000 sq. ft factory), we would expect a total staff of 30 to 70 employees, with about three quarters of employees involved in module construction, and one quarter in support or managerial positions. Factories with a smaller volume of production will have a smaller staff. For example, Vermod employs 20-25 FTE for a production of about one module per week.

The staff in a ZEM home factory will differ from a typical modular factory in terms of the organizational culture: the common goal is not to simply build a home, it is to build a ZEM home. This common goal affects every decisions and steps along the way. For example, an employee in a ZEM factory should know that every time they make a hole in the envelope, they are responsible for plugging it. Because of this cultural difference and need for attention to details at every step, there is an advantage to having a ZEM factory exclusively producing ZEM homes. ZEM factories may also more often rely on external experts for the design and verification phase of modular construction. For example, the designer may rely on a technical expert (internally or externally) that is familiar with Passive House design and modeling, and that stays in touch with latest energy efficiency technologies, to ensure the home will meet the expected ZEM specifications. In addition to QA/QC staff, the factory may also lean extensively on the energy raters that they use for third-party certifications, to ensure the ZEM home meets the ZEM design goals.

The example in Appendix VII provides a conceptual example of how the labor would be broken out among the trades and positions. In smaller factories, employees may hold more than one position, while in larger factories, each position would have a dedicated staff person. These staffing requirements will vary depending on the exact process flow, the number of stations and the standard module design. If stations are combined and crews perform more than one tasks, production will be slower, but staffing requirements will be lower.

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[16] Source*: Factory Design for Modular Homebuilding*, Michael A. Mullens, Constructability Press, 2011.

Using the estimated labor hours by task and trade and labor rates by occupations, provided in Appendix VII, a prospective factory developer can begin to estimate total annual labor costs. In addition, the following indirect labor positions will be required. In small factories, one person may fill two or more of these roles:

- General manager
- CFO
- HR director
- Accounts payable and receivable manager
- Purchasing manager
- Engineering manager/QA
- Production manager

## Lean Manufacturing

One key aspect of keeping costs low is to follow Lean manufacturing principles. Lean production methods focus on the value stream and reducing waste. Lean manufacturing principles call for constant improvements in processes, standardization, and the identification and remediation of all wasteful activity. The basic premise of lean manufacturing is to add value to the product as it moves down the line, reduce cycle time, and eliminate waste. Lean production principles need to be considered throughout the process, from sales, to design, to production. A lean production case study for Vermod is provided in the Case Studies section, to illustrate the benefits that can be gained from designing a lean factory. Lean designs can result in 50-80% waste reduction and production capacity increase.[17]

### TAKT Time

“TAKT” time is the average factory cycle time per module (hours/module, as an average of standard models produced at the factory):

Available Time for Production / Required Units of Production = Takt Time.

TAKT time is useful when planning a new factory because it helps assess the number of hours necessary for building a house, hence the number of weeks in production and workforce requirements. TAKT time will also help in the layout of work stations, to ensure a continuous flow of modules or crews throughout the construction process. This in turn will help determine the factory layout, to ensure that the layout allows for continuous flow. In line production, TAKT time determines the schedule when the modules move down the line. In crib construction, TAKT time is used to determine the frequency of rotation of crews. TAKT time can help estimate what the factory is capable of producing, how to balance workload, and identify if any tasks should be moved to the side of the production line to avoid bottlenecks.

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[17] http://www.1000ventures.com/business_guide/lean_production_main.html

### Efficient Production

Production is most efficient when orders are level, and production can avoid peaks and valleys, which tend to overburden people and equipment and lead to waste (e.g. fixing errors, overproduction, unnecessary movement of people and product, waiting, excess inventory, performing tasks that do not add value to the customer). Generally, operational performance is higher when product is standardized, and declines as more customization of modules takes place, because each new custom design may require a new process or steps that factory workers need to learn. More standardized module designs make it easier to plan and balance the workload among workers. Custom designs may put more unplanned work on some staff, and that overload may vary with each project.

> Production is most efficient when orders are level, and production can avoid peaks and valleys

Increasing production allows a factory to spread overhead costs over more products, rendering the products cheaper per unit. There are several ways to add capacity to a factory:

- Adding more hours to schedules, such as overtime for short term, or additional shifts for longer term
- Reducing cycle time and reducing bottlenecks (e.g. drywall)
- Reducing set-up time, so more staff time goes towards production
- Phasing capacity growth, using expansion walls, a flexible equipment layout, etc.

Even if production is not increased, increasing production efficiency can lead to cost savings. Production efficiency can be achieved by standardizing processes and activities. Efficiency can be improved by detecting and eliminating wasted time or resources from the following waste categories:

| | |
|---|---|
| Defect and corrections | •Defect and corrections needed to fix the defect (e.g. drywall cracks that need to be fixed down the line) |
| Overproduction | •Producing more than is needed or before it is needed |
| Motion of people | •Unecessary crew movements. Moving equipment closer together and reducing crews travel distance within the factory increasing the time available for production work. |
| Waiting | •For example, waiting. for upstream activities to finish, or for material, or for shared tools, or for malfunctioning tools to be fixed |
| Transportation of materials | •Unnecessary movements of materials or products. keeping workers, equipment, and materials in close proximity saves time. Movements that do not directly add value to the finished product (e.g. moving a pile of material out of the way to access other material) |
| Excess inventory | •Excess inventory and storing of material |
| Performing unnecessary tasks | •For example, unnecessary processes and paperwork that do not add value to the customer) |

**Figure 28: The eight types of waste considered in the lean process.**

The equipment and technology need to be reliable and tested before being incorporated in the production line. Customized designs that require the incorporation of new material or technology adds risk of delays and bottlenecks to the production line. However, building science and technologies are rapidly changing and factories need to have a process for integrating these as they become best practice.

Another way to lower production cycle time is to limit the time required for set-up at each station. This can be done by allowing some set-up to be done in parallel with the previous production run. Reducing set-up time for tools, material, and equipment is easier to do in a production line configuration than in a crib or bay construction configuration. In crib construction, the storage space around the module is more and requires more frequent set-up and break down of what crews need for each task. In a bay configuration, crews cycle through rather than modules flowing through stations. As a result, each time a new crew comes, and new activity starts, the set-up for the previous activity needs to be packed-out and the new activity set-up.

One of the key principles of lean manufacturing is to ensure that no problems are hidden. This can be done by ensuring that the factory is organized such that:

- The factory is orderly;
- All equipment is clean and ready to use;
- Items are sorted through and rarely used items discarded;
- The 3 items above are standardized and maintained over time.

### Reducing Bottlenecks

The goal of a modular home factory is to achieve continuous flow. Ideally, the modules should move down the production line in a synchronized flow, where all modules move to the next activity at the same time. This ideal may be hard to achieve due to process time varying between stations. Roofs and wall framing, along with drywall finishing are often bottlenecks in a production line. There are strategies that can help avoid blockages and bottlenecks to achieve a more synchronized flow:

- Incorporating queuing time into the flow;
- Planning buffers- reliable assignments that crews can do while waiting for the module if there is a backlog;
- Enabling workers to move downstream to complete work, or upstream to start early or help colleagues finish work. This helps absorb variations in cycle time;
- Incorporating flex workers throughout the plant that can work on any station to help complete tasks that are falling behind;
- Empowering all employees to inspect and identify defects and ensuring the worker responsible for the defect is notified immediately.

Lean manufacturing relies on value stream mapping, or identifying every value-added step in the production process. This can be done factory-wide, or for individual stations or steps. The end goal of value stream mapping is to eliminate steps that do not add value. Value stream mapping consists of the following steps:

1. Develop a sequence of critical tasks that form the lengthiest path through the project and what would result in the shortest time to complete the project. This is called the Value Stream Map;

2. Document critical performance metrics: quality, cycle time, productivity, inventory;
3. Observe, document, and analyze waste;
4. Pilot-test potential improvements, and fine-tune improvements;
5. Institutionalize the improvements;
6. Implement continuous improvement practices, through continuous improvement teams incorporating employees representing all levels of the company.

This discussion of lean manufacturing only touches on lean manufacturing principles. For a more detailed discussion of Lean methods, see Resources section.

## Manufacturing Flow Management and Customer Relationship Management

Depending on the sales plan and approach to customization, a modular factory could theoretically range from a “buy to order” supply chain where every house is customized and there is a long lead-time between customer order and home delivery. The other extreme is a “ship to order” model where there is no customization but short lead times and more economies of scale from producing a product with no customization of home features. In reality, ZEM factories are likely to be somewhere in between these two extremes. The supply chain strategy will depend on whether the approach allows for extensive customization or not. For a ZEM factory seeking to reduce costs and serving affordable housing, an approach limiting customization would be recommended.

Allowing for some customization can be useful to gain a lead in the market, but it’s important to set limits to the level of customization allowed. One approach is to offer tiers and levels of options for finishing details, rather than allowing for any customization the customer desires. With a tier approach, building material can be procured for each tier or package of options, without having to customize procuring the supplies for each customized project.

Production will generally follow these steps, from start to finish:

- Sales: inquiry to close (including lost sales)
- Design: standard designs or custom configurations
- Pre-build: design reviews, third party process (required for out of state production)
- Drawing packages with building specifications
- Production
- Pre-ship: final inspection
- Delivery: including set, punch list, on-site work
- Occupancy

**Generally, a factory will need to standardize the production with standard components and standard models, which will limit the impact of customization on the production line and schedule**. Having a well-established portfolio limited to the home designs that sell well (for established factories), or limited to a few models designed with a good understanding of what the target market wants (for start-up companies), will help maintain a smooth factory workflow and simplify the procurement process. A ZEM pilot can help drive demand. A pilot should be designed to build demand for a limited number of models.

A key principle of lean manufacturing relies on material being delivered just-in-time for utilization on the construction line soon after they are delivered. Orders and delivery schedules should be aligned with cash flow plans. Reliable supply of material is critical for a continuous workflow and production activities. Delays in delivery can result in bottlenecks on the supply chain, therefore there is a risk in relying on just-in-time delivery. Reversely, if production is behind schedule, supplier deliveries will build-up inventory level, and if production is ahead of schedule, there will be a shortage of parts. A ZEM factory should develop relationships with local manufacturers, especially if there are local manufacturers of products that are preferable from a health and environment perspective (see Appendix III: Building Material List for examples).

A ZEM factory is likely to order material from a number of suppliers including:

- Manufacturing (e.g. lumber, drywall, OSB)
- Retailers and distributors (e.g. windows, finished doors, pre-made cabinets, fixtures, HVAC, etc.)

Whether the factory can purchase materials directly from the distributor or will have to purchase from a retailer will depend on the structure of the supply chain for specific products, and the volume purchased. If the factory is purchasing large quantities, they may be able to bypass the retailers for products such as insulation material. However, unless the factory is large, the factory is likely going to be purchasing from retailers for windows, doors, HVAC systems, etc. If customization is more limited, the volume of each product purchased will be greater and the factory is more likely to be able to avoid the retailer markup and buy from the distributor directly.

#### Bulk Material

Typically, for bulk material that is used on every project (e.g. studs, drywall, etc.), there will be regular deliveries and a certain amount of inventory on hand at the factory to ensure continuous workflow. Contracts can be arranged with reliable local suppliers for just-in-time delivery. Using the same supplier for multiple components will help build a strong relationship with suppliers, simplify the ordering, and delivery process and may result in volume discounts from the supplier. The factory may need different strategies to manage each supplier, based on the volume of product purchased from each, and whether items are bulk supplies ordered on a regular basis, or specialty items that have longer lead time.

### Specialty Items

For specialty items (e.g. windows, HVAC systems, kitchen counters, etc.) orders will be project specific and a close relationship with the suppliers can help ensure deliveries are not delayed. There are a few ways to mitigate that risk:

- **Relying on multiple suppliers.** This approach may not be feasible for key products used in ZEM homes, such as specific triple pane windows, SIPs, and specific heat pumps and ERVs. Relying on multiple suppliers will complicate the planning process. If the factory has a good relationship with a supplier, this approach may not be necessary. This will need to be balanced with consolidating the number of suppliers as discussed above.
- **Safety stocks or buffers**. This approach works best if modules have minimal customization. For example, triple pane windows could be stocked if the same window models and sizes are used on multiple projects. Stocks and buffers are not aligned with lean production principles and will

need to be balanced with those principles. However, safety stocks may help mitigate risks of delays and bottlenecks.

- **Postponing construction of the module** until key specialty parts that would create a bottleneck are in stock.
- **Postponing installation of the specialty part** until that part is delivered. In this approach, the module could either continue moving down the production line until the part is available and the part be installed down the line, or the module could be pulled aside in a bay. For example, the module would be held from moving down the line until the customers decides on the countertops.

The ZEM factory will need to make decisions relative to what to buy pre-made and what to make in the factory. For example, the roof can be made in the factory, or can be purchased as SIPs. Similarly, stairs and decking could be produced at the factory and shipped, or built on-site. There will be a trade-off between costs and labor hours that will be factory- or even project-specific. If SIPs are not available locally, some factories have made them on site using a separate production line, others have used trusses instead of SIPs for the roof. Cabinets are another example of what could also be made on-site or ordered pre-built. The factory should ensure products are available before committing to offering that option. If no reliable supplier can be identified locally, the ZEM factory can elect to:

- Ship from far away, running the risk to have additional delays in supplying the product,
- Make the product on site, for example in a separate production line, or
- Find an alternative design for the home.

As with any construction business, it is important to vet suppliers and ensure that:

- The supplier will be able to produce or distribute the product;
- The lead time for the product is aligned with module production schedules and the deliveries will be on schedule.

It can help to visit the supplier’s factory to ensure the product quality will be as expected. As with any construction project, material should be inspected at delivery and defects and warranty issues should be dealt with at that point.

Factories should strive to manage demand and translate demand effectively into a smooth workflow. The production workflow and ordering process need to be aligned with how customer orders are handled, as well as how warranty issues are dealt with. For example, while a ZEM factory will be primarily focused on affordable housing, a ZEM factory may still be receiving orders from two main client types, and this will help balance the factory’s budget:

1. Well-informed, environmentally conscious early-adopters seeking customized homes at a higher price point;
2. Income-qualified residents in need of affordable housing and organizations representing them, with some of the orders coming in as bulk orders for a dozen homes or more.

The factory processes need to be able to handle both types of customers. For example, a start-up may receive orders from an affordable housing developer, but there may be delays in obtaining funding from various agencies that support the project, or in doing site evaluation for solar PV, performing the appraisal, etc.

The process need to be able to handle these delays in individual and bulk orders, for example by defining when projects get put into the schedule and material ordered. If the orders are put into the pipeline and the customer's funding then falls through or is delayed, this may disrupt the construction workflow. One approach is to only put the orders into the schedule once all financing has been approved and all grants received and to look forward and keep an eye on what will be in production two weeks ahead.

Factories may be able to cut down on material cost by entering into low-profits partnerships with suppliers that support the environmental and social mission of a ZEM factory serving affordable housing. A ZEM factory may also be able to secure grants for material substitution for healthier or more environmentally friendly products.

## Inspections, Quality Control, and Permitting

Quality inspections take place at the factory to meet different goals:

- Ensure that the construction meets the expectations of the design and specifications for the project;
- Confirm that the building meets building codes and certification requirements;
- Highlight energy efficiency and air quality attributes of the buildings.

Quality assurance (QA) ensures that a process has been designed and put in place that verifies that the product will meet set quality requirements. Quality control (QC) is the inspection of the product against set quality criteria. To meet these goals, quality assurance inspections take place at different points and through different avenues, as summarized in Table 6:

**Table 6: Quality assurance and quality control at the factory**

| Inspection type | Where and when in the process | By whom | Extent of inspection |
|---|---|---|---|
| **Internal quality assurance and quality control to ensure product meets design, specifications, and workmanship standards** | At each station, or after key steps in the construction process | Usually, internal staff, e.g. in-house dedicated inspector, or plant manager. It can be someone with lots of experience or a plant manager or more of an engineering background. It is important that the internal QC staff is disconnected from workers performing the work, to provide honest feedback. | Each station has a QC manual that the workers follow. The inspector reviews the work and communicates any issues to the workers a that station. A blower door or duct blaster test may be done early in the process on a voluntary basis to fine-tune the QA/QC process, but once the expected quality is met routinely, it is usually no longer necessary. |

| Inspection type | Where and when in the process | By whom | Extent of inspection |
|---|---|---|---|
| **Quality assurance for code compliance verification** | As defined by building code, usually at rough-in and after key systems are installed, e.g. electrical, plumbing, HVAC, etc.<br>At the design phase, construction phase, and after the house is finished, as locally required | Local code enforcement official, or third-party inspector if the final house site is too far from the factory, or if there are specific requirements to use a third-party inspector | Inspection includes electrical, mechanical, plumbing and building aspects, to ensure all the work done is in compliance with the rules and regulation specified in the building code<br>Completes the final occupancy inspection and issues a Certificate of Occupancy for the project if no code violations are noted in the building code |
| **Home certification/labeling verification to obtain recognition for energy efficiency features** | Depends on program, some like PHIUS Passive House label require a review of designs<br>Often an inspection is required after insulation is completed, but before the walls are closed up (Thermal Bypass inspection)<br>Final inspection once the home is complete and set on site | Third-party independent inspector or rater. The rater's qualifications will vary depending on the specific labeling program (e.g. LEED, Energy Star, PHIUS+) | Final inspection usually includes a blower door, duct blaster, and ventilation flow checks. |

## State Requirements in New York

- ### Factory Licensing

Construction businesses in New York State are regulated at the local and municipal level, and a general contractor license must be obtained from the local government. Each municipality has its own licensing requirements. A construction business is also required to register with the Secretary of State.

Construction businesses must obtain home improvement contractors licenses to work in the cities of New York, Buffalo, Yonkers, and Long Beach and in the counties of Suffolk, Nassau, Westchester, Putnam, and Rockland. However, in most counties, construction of a new home is not considered a "home improvement".

- **Modular Home Insignia of Approval**

Under the definition of the NY Division of Code enforcement, a modular home is “a factory-manufactured dwelling unit conforming to applicable provisions of the New York State Uniform Fire Prevention and Building Code (Uniform Code) and bearing insignia of approval issued by the Secretary of State of New York State.” Modular homes are regulated by Part 1209: *Regulations and Fees for Factory Manufactured Buildings*.[18] In Part 1209, manufactured buildings are defined as:

*Factory manufactured home means a structure designed primarily for residential occupancy, constructed by a method or system of construction whereby the structure or its components are wholly or in substantial part manufactured in manufacturing facilities, intended or designed for permanent installation, or assembly and permanent installation, on a building site.*[19]

There are two methods by which modular building plans may be approved by the Department of State (DOS):[20]

- An application may be submitted for approval of a new individual model or system subject to a full review performed by the DOS. This may take 3 to 4 weeks for an initial response.
- A new individual model may be submitted to the DOS for approval following an application under the third-party review program, subsequent to a review completed by an approved third-party review agency. Generally a review performed by the DOS under this program is limited to checking for compliance with established submission standards and code review.

Details and full regulations to obtain an insignia of approval for a modular home can be found in Part 1209: *Regulations and Fees for Factory Manufactured Buildings*.[21]

**Local jurisdictions may also have specific requirements for housing intended as rental housing.**

## Healthy Buildings Materials

For affordable housing to be successful, it needs to provide a healthy environment for its occupants, require little maintenance over time, be resilient to extreme weather events, and be built of components that are long-lasting.

It is important to use building materials that are not harmful to health for two primary reasons:

- To maintain good indoor air quality in the home. Along with a home design that eliminates moisture and mold risks, and provides optimal ventilation, using products with low volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), and formaldehyde emissions will ensure good air quality in the home, and reduce health risks for the occupant (e.g. asthma). Limiting the use of non-volatile toxic substances is important as well, as those can be inhaled as dust or absorbed through hand-to-mouth contact in young children.
- To protect the air quality in the factory. Eliminating the potential harmful product from production should be favored. The impact of harmful products that cannot be eliminated from production can be mitigated with personal protection equipment and adequate ventilation.

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[18] https://www.dos.ny gov/dcea/manufinfo.htm
[19] https://www.dos.ny gov/DCEA/pdf/Active%20Cert%20List%20MFG%20Housing%2011082017.pdf
[20] https://www.dos.ny gov/dcea/fmb_si.html
[21] https://www.dos.ny gov/dcea/manufinfo.htm

In 2018, the Healthy Building Network conducted a review of some of the building material used at the Vermod factory, a ZEM factory located in Vermont. A summary table of their findings and recommendations is in Appendix III.

## Factory Location and Demand for ZEM Homes in New York State

VEIC performed a market analysis of New York State and based on housing trends and market capacity research estimated that 10,000 ZEM homes could be installed in the state. There is a dire need for quality affordable housing in the state of New York. This could be accomplished by replacing and displacing existing and new homes with ZEM homes with a production ramping up to 1,800 ZEM homes per year by 2030. The market potential in New York State is more fully discussed in Volume 1: *Market Analysis for ZEM in New York State*.[22] To select the location of a potential ZEM factory, it can help to look at the location of resident-owned parks, as they could be the primary target of a pilot ZEM mobile home replacement program. It is also helpful to look at the location of existing plants that would be able to produce ZEM homes. This information is provided in Figure 29. A factory located near Highways 87 and 90, for example, would be able to serve the eastern part of the State for a ZEM pilot. As additional resident-owned parks are established, private owners identified, or affordable housing partnerships secured, additional ZEM factories can be developed to serve that geographic location.

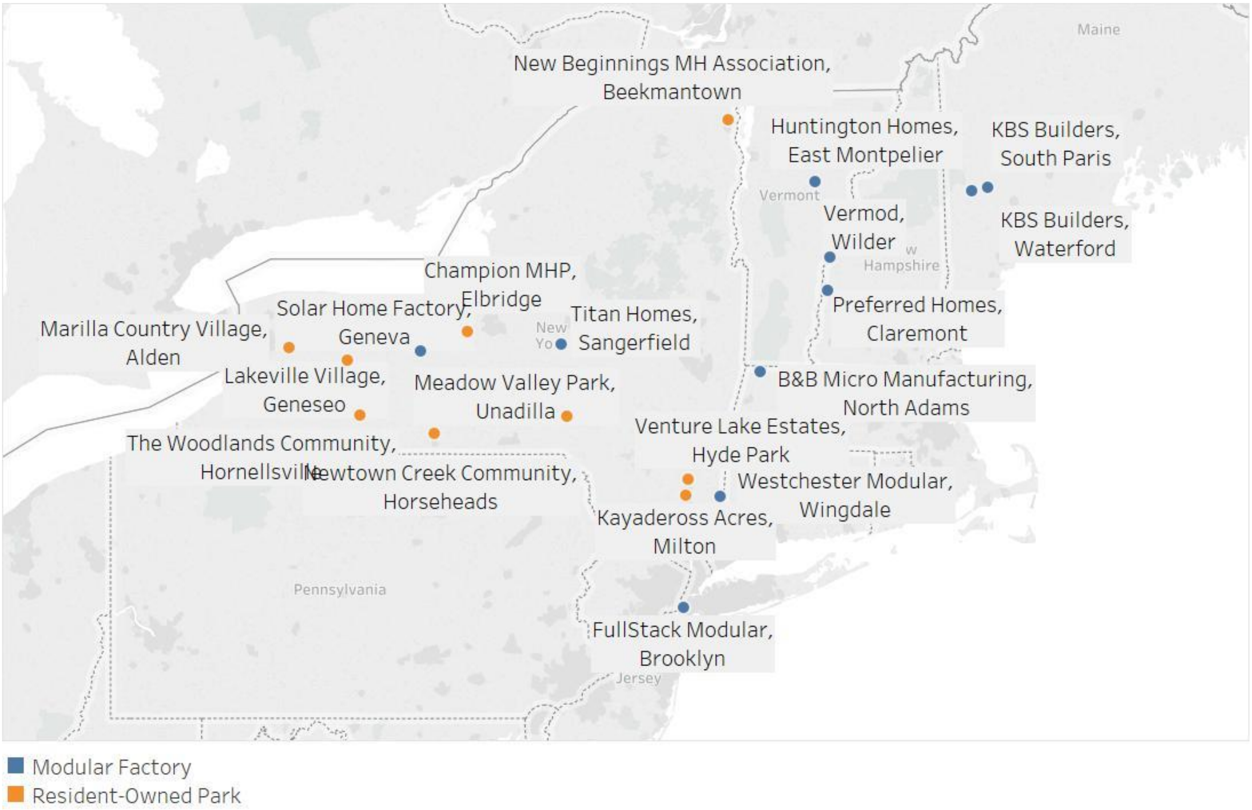

**Figure 29: Location of resident-owned parks and existing modular factories.**

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[22] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

Factory size and workforce can be estimated, recognizing that values will vary depending on production processes and factory set-up. Using the conceptual factory sizes in Table 3, to produce 100-500 homes annually in New York State (assuming 2 modules per home), ramping up to full production capacity, there would need to be 2-10 start-up ZEM factories by 2024. Between 2024 and 2030, assuming a demand increasing from 500 to 1,800 homes per year, some of the start-ups would need to increase production and a few additional factories could be built in different areas of the state. By 2030, the ZEM market could be served by the expansion existing ZEM factories and the development of a few larger factories serving the whole state.

Deciding on whether to favor several smaller factories over one larger one will depend on a balance of several factors:

- Production costs: larger factories generally producing cheaper modules;
- Transportation costs: several regional factories generally transporting modules shorter distances than one large factory;
- Labor availability: one larger factory may have difficulties hiring the necessary workforce, depending on location;
- Local economic development: benefits of a small factory supporting the local housing demand and need for jobs vs a larger, centralized factory serving a larger region.

Plant capacity as designed may be different from the actual production per day, due to labor shortages, orders being over or under expectations, and the peak and valley inherent to varying demand and production over time. Variability in production rates and labor hours will also be associated with varying housing specifications, degree of customization, and the percentage of the home that will be finished in the factory, vs. finished at the site.

## Business Structure Options

The ZEM factory can play several roles in producing and selling homes. Each approach has benefits and drawbacks (Table 7). Recent trends indicate that more and more factories chose to act as dealers for the region where they are located. Some factories are also playing the developer role, delivering homes to communities created with a factory's specific home design in mind.

**Table 7: Pro and cons of business approaches**

| Business roles | Pros | Cons |
|---|---|---|
| **Factory only—constructs modular homes** | • No need to have a design center at the plant.<br>• The inventory can be moved to dealers. | • Retailers can significantly add to the cost of a home, depending on their mark-up.<br>• Missed opportunity to market the brand to the customer through factory tours. |
| **Dealer/ retailer as well— designs and sells homes directly to customers** | • Avoids retailer markup.<br>• More control over the use of the brand.<br>• Direct contact with customers to support marketing and word-of mouth. | • Factory needs additional staff to sell homes, manage home design, and marketing. |

| | | |
|---|---|---|
| **Developer as well— purchases land, develops land, sells to customer** | • Create demand as well as supply homes through housing developments. | • Additional distinct business model to develop, grow, and manage. |
| **General contractor as well— prepares site, sets and finishes the home. May also own the transportation fleet (optional)** | • Ensures installations are performed appropriately.<br>• Avoids contentious assignations of responsibility for problems | • Additional skill set require.<br>• Manage labor, material ordering, and many aspects of site work. |

Business structure will impact taxes, ability to raise money, business registration paperwork, and personal liability. It can be helpful to consult with business counselors, attorneys, and accountants to choose a business structure.

- **Sole proprietor**: this structure does not produce a separate business entity; the business owner can be held personally liable for any business debt and obligation. This is a good option for low-risk businesses and may not be the best option for a ZEM factory, which may have a risk of significant debt and obligations.
- Partnerships:
    - Limited partnerships;
    - Limited liability partnerships: this structure protects each partner from debt against the partnership, and partners won't be held responsible for the actions of other partners.
- **Limited liability company (LLCs):** LLCs protect personal liability and, in most cases, personal assets in case the LLC faces a lawsuit or bankruptcy. LLCs can be a good choice for medium- or higher-risk businesses, or owners looking for certain tax advantages compared to a corporation.
- **Corporation (C Corp):** a C Corp is a legal entity that is separate from its owner, offering stronger protection for the business owner, but at a higher cost, and more detailed record-keeping and reporting. Corporations can raise capital through the sale of stock.
- **Non-profit corporation (501(c)(3) corporations)**: Nonprofits do work that benefit the public and for that reason, are tax-exempt. Non-profits must follow similar rules as corporations. Non-profit status allows the business to re-invest net profit into increased production. Non-profits may not have direct access to any available economic development tax credit incentives.
- **Cooperative**: this business structure allows for an organization to be owned and operated for the benefits of those using its services, or by its employees.
- **Public sector**: for example, educational organization, such as community college, vocational school, etc.

**Public-private partnership (PPP or 3P, or P3):** There is no consensus on a PPP's definition. PPPs can be understood both as a governance mechanism and a brand. Generally speaking, with a PPP:

- The infrastructure need and proposed solution originates from the public sector.
- The project design, financing, and construction is done by the private sector.
- The operation and maintenance and ownership falls back on the public sector.

PPPs allow for sharing of the risk and the development of innovative solutions. PPPs often involve a long-term contract between a public sector authority and private business. In projects aimed at producing public goods, the public sector may provide a onetime subsidy or grant, or tax breaks or guaranteed revenue, to make the project financially viable.

### Subsidies, Tax Credits, Grants and Loans Available

A number of incentive and tax credit options may be and will contribute to determining the location of a ZEM factory. Incentives may be available for brownfield development or there may be redevelopment funds available. Regional development agencies are usually available to assist in site selection based on economic development incentives and New Market Tax credit (NMTC) available locally. Incentives may reduce start-up costs enough to be a significant factor in site selection.

Many states have a tax-credit-based incentive program for the development of businesses that lead to job development in state. For example, New York state offers the following programs through Empire State Development. Tax credits are typically not directly applicable to non-profits, that do not have sufficient tax liability, but a partnership with a private entity (e.g. a LLC tax partner) may be possible to gain access to these incentives. The following programs may be applicable to a factory developer in New York State:[23]

- **Excelsior Jobs Program**, which qualify businesses for tax credits for each job created. Manufacturing firms creating at least 5 jobs are eligible. The program offers:
    - Excelsior Investment Tax Credit
    - Excelsior Real Property Tax Credit, for businesses locating in economically distressed area, or in industries with higher employment and investment thresholds.
- **Regional Council Capital Fund Program (ESD Grants – REDC**), which offer grants to private businesses, non-profit organizations, and others, for capital investments that result in job creation. Examples include acquisition of land, buildings, and equipment; soft costs and planning and feasibility studies related to a capital project.
- **START-UP NY**, which offers tax-based incentives and innovative academic partnerships. The program offers the opportunity to operate tax-free for 10-years on or near eligible university or college campuses in the state.

Empire State Development maintains a directory of small business programs available in the state, including programs relating to: [24]

- Technical assistance
- Funding Incentives
- Industry-specific programs
- Workforce recruitment, development, and benefits
- Government contracts and market expansion, and

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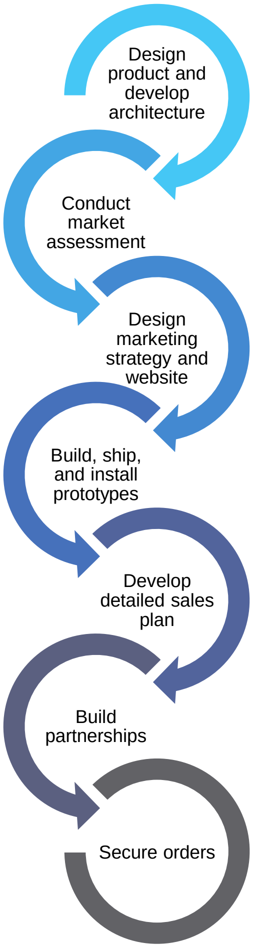
[23] https://esd.ny.gov

[24] https://esd.ny.gov/sites/default/files/SmallBizDirectory_Jan2019.pdf

## Getting started: Pre-Launch Preparation and First Three Years

To start a factory, the following steps need to take place. Depending on the business structure, factory size, and demand some of these steps may be omitted or the order of the steps may vary, and many of these steps will happen in parallel (Figure 30). When deciding upon a certain ramp-up strategy, factories will need to consider utilization, product variety, ramp-up time, and decoupling level (e.g. what standard components to produce prior to the customized order):



**Pre-launch:**

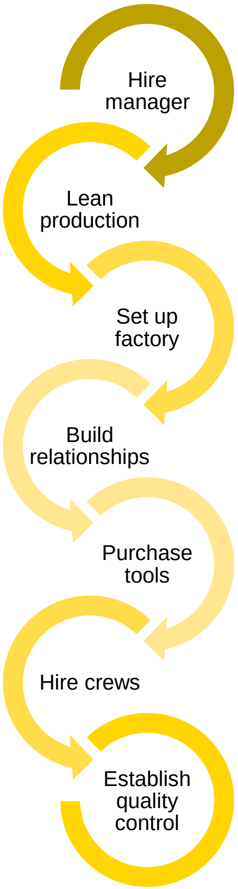
1. **Design product and develop product architecture.** Designs should be in alignment and compatible with Lean production principles. Start with only a few floor plans and expand to more plans as demand and production picks up.

- **Conduct market assessment**. Conduct a market analysis of the potential demand for ZEM homes, this will help determine the size and configuration of the factory. These markets studies have already been conducted in a few states and are publicly available. If demand is approximately 50 homes or less per year, then “Crib” or “Bay” construction may be the best fit. If market demand is expected to be more than 50 homes per year, then it may be worth considering line production, which has the potential to lower costs and speed up production time per module.
- **Develop business plan and raise capital** for new factory and field installation operations (if vertically integrating site preparation and setting the home).
- **Design marketing strategy and website.** The website will serve two purposes: a sales tool for home buyers to advertise the final product, and a communication tool with affordable housing partners and investors**.**
- **Build and ship prototype(s), hire sub-contracting installation crew (if needed), install prototype(s)**. First the company will design, build and install one prototype home in the targeted market area. This prototype will be built through another modular home factory as the new factory will not be up and running yet.
- Develop detailed sales plan.
- **Build partnerships with affordable housing** providers, land trust, and other organizations.
- Develop detailed capacity plan and production processes. Estimate labor requirements and cycle time.

- **Secure orders**, using the home prototype as marketing tool.

In addition to the pre-launch tasks listed above, there may be a need to train the local workforce to ensure sufficient staffing levels at the factory. The ZEM factory could work with the local community college or technical school to develop a job-training program that would ensure long-term availability of qualified workers.

**Factory set-up** (several of these steps are likely to happen concurrently)**:**



- Hire factory manager.
- Engineer a Lean production factory.
- **Set up the new factory**. The factory general manager will select the factory site and lease, purchase, or build the factory. The factory management team will then set up the equipment, purchase the inventory, and hire line leads and crews for the factory and field installation. The management team will also seek local partners for the initial field installations.
- **Build relationships with suppliers** of material appropriate for ZEM production.
- **Purchase tools and hire permanent crews.** Once there are firm orders for roughly 1/5 of the expected production for year 1, with substantial commitment for more from affordable organizations (roughly four times as much during the first year of production), the new factory should be staffed with dedicated staff.
- **Establish quality control, quality assurance** protocols and hire a third-party, independent quality control agency, if necessary.

Once a factory has been secured, a start-up can choose to hire sub-contractor crews to get the business off the ground. Planning on an increase in demand, the factory can then purchase tools and hire a permanent crews once sufficient orders have been secured. Sub-contracting teams can provide the tools required for their crafts. However, finding the right subcontracting crew might be challenging, depending on the region, and the crews will likely need additional trainings and close supervision, to ensure they build all details according to ZEM specifications.

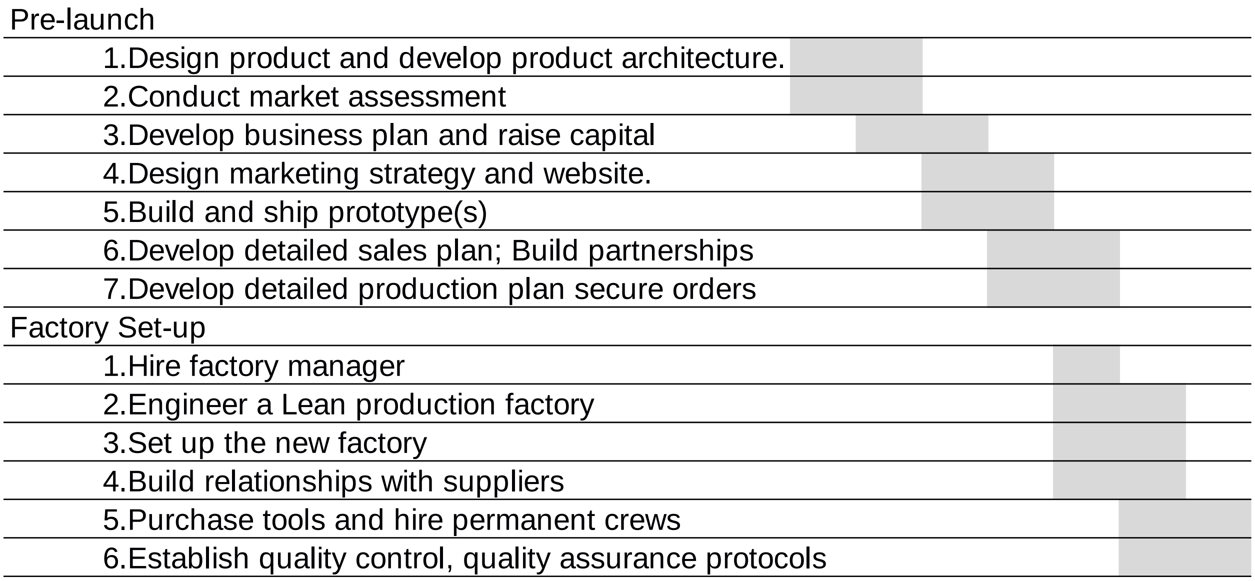


**Figure 30: Getting started Gantt chart**

## Working with Affordable Housing Providers

New York State has an extensive network of for-profit and nonprofit affordable housing developers that could potentially purchase and redevelop a manufactured home community with ZEM homes using either an ownership or rental model. More details are provided in Volume 1: Market Analysis for Zero Energy Modular Homes in New York State.

### Roles and Responsibilities

In the standard modular home market most customers purchase from a dealer. Dealers may procure homes from several manufacturers. In a vertically integrated modular company, the factory sells directly to the customer. This model is becoming more common, especially when the factory is well established, and has a recognizable name and brand, with an associated quality expectation. Generally, the dealer, developer, or factory designs, prices, and orders home from manufacturer. Once the home is manufactured, the General Contractor (GC) turns that home into a livable home. The GC is responsible for site preparation (foundations, etc.) and setting and finishing the home. Many dealers and manufacturers also function as GC or are closely affiliated with GC. It can be tricky for modular home factories to work with GCs not familiar with modular, as there is not much educational material available, and some specific knowledge of modular buildings are needed to properly set and finish the home.

When working with affordable housing, the ZEM factory will sometimes serve as dealer, designer, manufacturer, and/or GC for setting and finishing the home on-site.

By not selling homes through a separate dealer and making deals with affordable housing providers directly, the ZEM factory can cut on costs associated with this intermediary. Partnerships with affordable housing, land trust, and other community organizations replace the traditional sales department of a for-profit modular home producer. The partnerships will facilitate bulk purchase of houses. ZEM can also work for tribal and other groups. The partnership approach will result in very low marketing costs, limited to a website and brochures.

The affordable housing partnership approach between the factory and the housing provider will result in very low marketing costs, limited to a website and brochures. If homes are sold directly to home owners as well, then a more substantial marketing effort will be needed. In some cases, such as Habitat for Humanity projects, a volunteer workforce can be expected to contribute to the construction of the home, which can help lower costs. That volunteer workforce can contribute to finishing the home once it has been set on-site. In a Habitat-owned factory model, if the factory were located near a housing development project, volunteers would also be able to help in the factory.

### Designing with Affordable Housing in Mind

For ZEM housing to be successful and accessible to affordable housing providers, it needs to **provide affordable, durable, and low-maintenance housing.** Pricing needs to be competitive compared to stick-built zero-energy housing. Grants and subsidies can help bridge some of the difference, but financial support should be expected to launch this new market and the product needs to be able to sell itself once the market is established.

Re-using designs allows the factory to avoid design and permitting costs.

For ZEM to keep costs low and keep homes affordable, factories will need to focus on mass production and limit customization. Limited customization not only improves production efficiency, it also reduces design costs. Re-using designs allows the factory to avoid costs related to designers, architects, engineers, inspections and inspection stamp costs. In reality, a certain degree of customization will always take place with each home but setting boundaries on that customization will be necessary to keep costs low. Limited customization also simplifies permitting and approvals, instead of each design needing a review and approval, a design kit can be approved instead.

For affordable housing to be successful, it needs to:

- Provide a healthy environment for its occupants,
- Require little maintenance over time,
- Be resilient to extreme weather events, and
- Be built of components that are long-lasting.

It is important that the houses are well-designed and well-built with these criteria in mind. A healthy environment for the tenants and workers requires choosing healthy building materials, limiting materials emitting VOCs, air sealing properly to avoid condensation and mold issues, and providing sufficient ventilation.

Additionally, house designs should be available that are compliant with universal design criteria:

- Accessible to all regardless of age, size, abilities, and disabilities
- Allows owner to age in place
- Provide step-less entrances, wider hallways, larger doors. Standard hallway in modular homes is 36 inches, accessible hallways would have 6 inches added.
- Include user-friendly items, such as door handles and faucets

- Allow sufficient room for a chairlift or elevator in stairwells
- Offer roll-in showers, tub with transfer seat

### Other Strategies to Keep Costs Low

- Streamlining and standardizing communications to and between crews, engineers, designers, and management can result in better quality and more efficient production.
- The factory itself can be made more energy efficient: smart factory and retro-commissioning are strategies that can help reduce overhead costs.
- With higher production volumes and greater production efficiency, price points should decline, thanks to fewer FTE per module, lower costs materials due to higher volume contracts.
- Transportation and finish costs could be minimized (and quality increased) if these are internal capacities rather than subcontracted responsibilities.
- Including solar PV panels at the factory can lower energy bills. The additional installation of batteries can also help lower peak demand and thus can bring the factory to a lower rate class, lowering electric bills.
- There may be tax and other government incentives available for building energy efficient housing or affordable housing, for making the factory more energy efficient, or for starting a factory in an economically depressed or rural area. Grants and incentives are listed in a prior section and should be thoroughly researched and utilized to lower overhead and production costs.

## Examples of Affordable Housing Projects

### McKnight Lane Park, Waltham, VT

In May 2016, the Addison County Community Trust (ACCT) and Cathedral Square developed a new 14-unit development in Waltham, VT. The duplex ZEM homes were designed by Pill-Maharam Architects and constructed by VERMOD Homes. More information can be found at: http://www.addisontrust.org/mcknight-lane.html

### New York City Urban Infill Project

Vermod was commissioned to provide 13 Urban infill ZEM homes in New York City. The Habitat for Humanity homes will be built in 13 small lots scattered through Queens. The homes will then be sold to income-qualified buyers through a lottery. The homes will be delivered with all finishes and appliances in place and will be fitted with solar panels. Finishing the home on-site will take about one week and will result in minimal disturbance for neighbors.[25]

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[25] https://vtdigger.org/2019/01/16/making-vermont-vermont-homes-will-move-new-york-summer/

## Factory Case Studies

The following case studies provide examples of existing and potential ZEM factories, that illustrate the various approaches that can be taken in developing a ZEM factory business model.

### Factory Start-up: Solar Factory in Geneva, NY

***Factory Size and Location:*** *Start-up Bay Construction Factory in Geneva, NY.*

***Approach and strategy**: Factory acts as developer as well.*

Solar Home Factory manufactures fully finished modular homes with net-zero or net-positive energy use. Solar Factory is currently developing the Lake Tunnel Solar Village in Geneva, New York — a development of 20 zero-energy homes of 650 to 1,000 square feet each.[26]

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[26] https://www.laketunnelsolarvillage.com/; images from https://www.instagram.com/solarhomegeek/

## Factory Start-up: Leaf Prefab Factory in Malone, NY

***Factory Size and Location:*** *10,000 Start-up Bay Construction Factory in Malone, NY.*

***Approach and strategy****: Bay construction using casters to move modules, access the underside, and move the modules.*

**Figure 31: Leveling and tipping casters.**

Tim McCarthy started a small ZEM factory in Malone, NY in 2018-- Leaf Prefab. Leaf Prefab builds both modules and panels.

After Leaf Prefab's first home was built at another factory location, the production was moved to a different, more suitable building. The building now consists of 10,000 square feet, rented at a very favorable cost. The adjacent 60,000 sq. ft. space is vacant and is available to Leaf Prefab for expansion if the factory were to grow.

The modules will be produced on casters, which will allow the modules to be moved around the factory floor, and rolled out the door onto a loading ramp and onto twin I-beam shipping frames for delivery to the customer. A much larger door than the existing loading door will be retrofitted into the building, which will allow modules to be simply rolled out for shipment.

Heavy duty leveling and tipping casters (costing around $140 each) will be used as a strategy to move the modules around the factory and to tip the modules to access the underside, to fully finish the underside of the first floor, or to access the bottom side of panels. Leaf factory is currently testing this tipping caster approach before implementing it throughout the production.

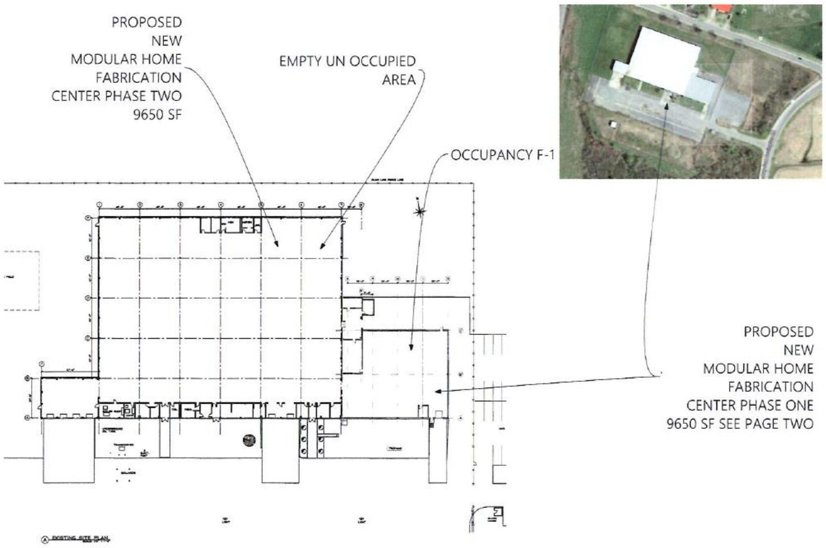

**Figure 32: Leaf Prefab factory.**

## Vermod Factory, Wilder, VT - Lean Manufacturing Improvements

***Factory Size and Location:*** *20,000 sq ft bay construction factory in Wilder, VT.*

***Approach and strategy****: The factory exclusively builds ZEM homes, shipped to Vermont and neighboring states. The factory has sought to maximize efficiency through Lean manufacturing improvements.*

In 2013 Vermod started producing ZEM homes with a 10-homes pilot project. As of today, Vermod has set over 90 ZEM homes around the state and employs 15-20 local employees. Partnering with Efficiency Vermont's Zero Energy Modular (ZEM) Program, Vermod provides affordable housing for low- and moderate-income Vermonters with a special focus on replacing mobile/manufactured homes with ZEM. The case study at Vermod Homes demonstrates a bay style construction environment. Their specific example produces 20-30 homes a year. Their five-bay operation could be expanded to 50+ homes if demand increases and staffing is available.

In 2018, Vermod embarked on a LEAN manufacturing effort to improve the efficiency of their production. Vermod started as a construction business moving into a "factory" space with the intent to build multiple ZEM homes at a time. As a startup business, many systems were developed as needed without structure to replicate the process. The strength for Vermod was the knowledge of ZEM and construction in general. The challenge for Vermod was infrastructure, systems, discipline, and all other aspects associated with a startup. The first step in the journey to move from the current state towards the challenge defined earlier was to start looking for waste in the processes at Vermod.

- Using Lean Organizational techniques and visual systems, everything was sorted, what could be used was organized visually on shelves and labeled with Min/Max levels. Unnecessary items were disposed of appropriately. Space was reclaimed for staging received material for active projects.
- One project completed was the transformation of a saw used for cutting floor joists. This saw had been a permanently mounted tool located in one corner of the shop. The cuts were made and then moved to the bay to be installed. Vermod shop personnel rebuilt the saw base and made it mobile on big wheels so that the saw could be moved to the work area. With this new setup, the framing personnel do not need to leave the work area to get the raw materials and cut them for installation. This is just one example of how Vermod has installed their tooling and materials on rolling carts in order to bring them to the module being worked on.
- In order to reduce this waiting time Vermod began working on the hand-off process from the front office to the shop floor. Formal design review meetings began where the trades could all look over the prints looking for any conflicts with their work, and verify materials and look over the design for manufacturability. Only after a proper design review and proper sign-off of all parties shall a design be released to production. Upon release to production, a project will be assigned a bay 6 weeks out in order to allow long lead time materials to be ordered and received.
- Vermod does its best to stagger work in the bays so that it is at various levels of completion so that different crews are working in different bays at any given time. However, this has been a

challenge for Vermod. Financially, given the current workload, the decision was made to maintain the current staff level and limit production to three bays. The idea was to focus on the three bays, implement the Lean changes Vermod had been working on and getting really efficient as a three-bay operation before scaling up to the five bays.

- Before implementation of the lean manufacturing improvements, Vermod was experiencing an excessive amount of rework due to problems not being caught early in the process, such as sheetrock issues. The lean production focus became to follow a third-party standard across the board, with a focus on Quality at the Source: personnel at each process step make sure the steps before were completed without defect. If they find a defect, they pass this information back to the upstream process to mitigate future problems. Everyone is accountable and feedback is given in a constructive way with the goal of always improving the process. Vermod Homes has adopted a quality standard that aligns to third party inspection, which is required for out-of-state sales. When a modular home is built out of state, local inspectors require that a third-party inspection service act as that on-site inspector to ensure that the out of state build process meets all local codes and requirements. Many states within Vermod's delivery range, such as Massachusetts, Maine, New Hampshire, and New York, all require third party inspections. This process requires that Vermod send detailed drawings for all stages of production. These drawings are then reviewed and stamped to define the specific methods that will be used to produce the home. Then, the third-party acts as an on-site inspector at specific stages of production. The checking system that results allows the work to be validated as it's progressing and provides constructive feedback to the people responsible for catching and eliminating mistakes and rework.
- In order to minimize excessive design iterations with customers pre- and post-contract, and to give the customers a stronger starting point, the idea of the Book 1,2,3 designs was introduced. Each book is based on tiers of designs from income-qualified, minimal customization and size limitations in Book 1, to slightly bigger two-box designs with a little more customization in Book 2 to fully customizable homes in Book 3. Book 1 or 2 designs being less customizable require less of a deposit than the fully customizable Book 3. This initial education with the customer and clarification of design parameters helped to streamline the design process and decrease design time while the customer still gets what they want and can afford. Unlike traditional home building process, changes should not be made during the build process to keep timeline moving.
- Waste of Transportation comes from excessive transport of parts and materials around the plant. Vermod has some great systems to limit this. Each bay has a storage area at the end of the bay where all materials are stored upon receipt. Any time material is received that is job specific it is put in a bin and stored on those shelves at point of use. There is no need to move it more than once.

Efficiencies can be increased in several areas, for instance, by purchasing pre-fabricated materials from the supply chain, or building subassemblies of common building details. However, this low volume, high variability bay configuration still moves people to the work, instead of moving the work to the people. High efficiency operations can only be developed by significantly limiting the variability of model choices. In addition, the volume must be increased by a factor of 10 to achieve the kind of efficiencies that true flow manufacturing could offer. More details on the findings of the lean improvements at Vermod can be found in the full report, which can be requested from VHCB.org and VMEC.org.

## Community College and Career Technical Educational Model

***Factory Size and Location:*** *Proposed 10-20,000 sq. ft in Boulder, CO.*

***Approach and strategy****: The factory will employ students and will provide an educational opportunity as they build ZEM homes for local, affordable housing needs.*

**Figure 33: Potential locations for a 10,000 sq. ft crib construction factory at Arapahoe Ridge High School.**

Several community schools, technical and vocational schools have expressed an interest in starting a Crib construction factory, where students could work on ZEM homes throughout the semester. The homes built in those factories will be designed by an architect firm in such a way that they can be zero energy ready. The homes will then be built by the students to meet all state and local regulations.

Students will learn to build all the components of a home indoors, and the house will ultimately be delivered to an affordable housing project locally.

Two examples of that type of projects are Boulder TEC, Boulder Valley School District in Colorado (led by Michael Bautista) and Smith Vocational in Massachusetts.

Building the homes in these small school-based facilities will have a few benefits:

- Educate students toward high efficiency construction and trades
- Replenishing the workforce with skilled trade
- Allow for partnerships with Habitat for Humanity, and donations of material
- Provide a student labor force at no direct labor costs
- Ability to get free materials and equipment from sponsorships, keeping upfront costs low
- Working through the school district opens doors for grant opportunities

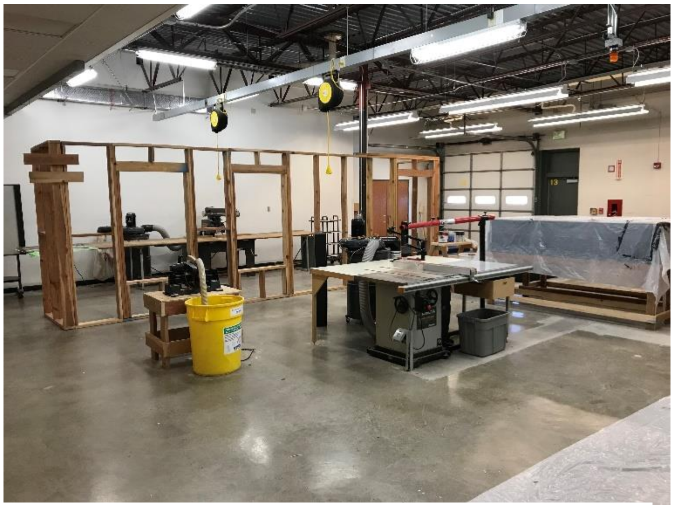

**Figure 34: Teaching space at Arapahoe Ridge High School.**

However, there are also some drawbacks to this approach:

- Factory production volume will be low, probably 1-2 homes per year
- Truck maneuvering for home delivery may be difficult on school grounds and will need to be carefully planned

## Potential ZEM Factories:

### St Regis Mohawk Akwesasne Homes, New York

***Factory Size and Location:** To be determined*

***Approach and strategy**: Opportunity for a tribal authority to own the factory as well as act as the developer of housing for tribal communities.*

The goal of the project is to "create an Eco-village called Akwesasne Homes to counter the housing shortfall, amplify community and cultural cohesion and be more resilient in the face of increasingly erratic economic, climate and pollution events facing the Akwesasne Mohawk tribal community." An initial plan calls for about 44 units and a building to house the Boys and Girls Club. This housing need could be fulfilled with ZEM homes, built in a factory owned by the St Regis Mohawk Akwesasne Tribe.

### Disaster Recovery

***Factory Size and Location:** To be determined.*

***Approach and strategy**: Potential for ZEM homes to be used for disaster recovery, through one central factory producing ZEM homes to be deployed as permanent housing replacement following a natural disaster.*

From 2005 to 2007, Healthy Building Network (HBN) developed a business plan to build what they called the "Unity Homes". While the factory never came to fruition, it would have been located in Columbia, Mississippi, to provide rebuilding of low-income homes with quality ZEM homes following recent hurricanes. The factory had been planned for 86,250 square feet with 14 production stations that would have produced up to 4 modules per day, 500 houses per year by the third year of operations. Floor layout would have been as sidesaddle with staging and subassemblies on each side. Plant designs called for a 375' by 230' factory (Figure 35).

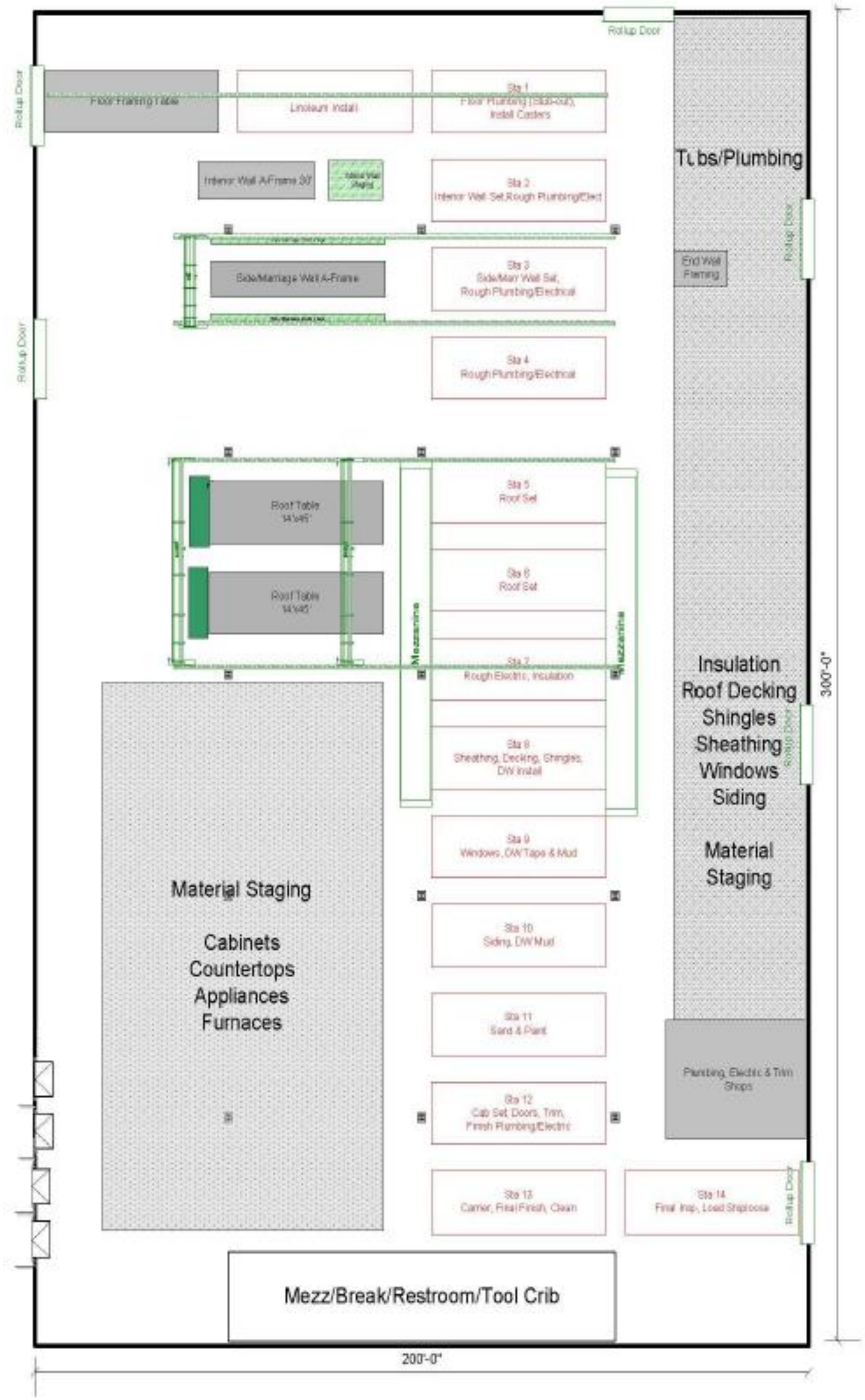

**Figure 35: Healthy Building Network "Unity Homes" factory layout.**

# Conclusions

There is significant interest in and potential market for ZEM as an alternative to manufactured housing and single-family homeownership or rental, but the limited capacity for building ZEM homes is the most significant barrier to advancing this housing solution. This manual serves as guidance and resource for supporting the development of additional ZEM factories nationwide.

The development of a ZEM factory can take many forms, from a small, local, crib construction factory, to a large, state-of-the-art highly efficient factory serving a large area. Start-up may favor a crib construction design that involves less upfront capital, while factories with enough capital may choose a line-production layout that results in production efficiencies and lower production costs

In spite of their differences, ZEM factories will all share common attributes:

- Homes with high insulation, an air tight envelope, balanced ventilation, and minimal space conditioning
- No or low energy bills for the residents
- The creation of manufacturing jobs in rural areas
- Affordable, quality homes installed in partnership with affordable housing partners

Regardless of the factory business plan, size and layout the creation of supportive programs and financing sources from a state or federal agency would help support the development of the ZEM market for affordable housing.

# Resources

- Volume 1: Market Analysis for Zero Energy Modular Homes in New York State http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state
- *Factory Design for Modular Homebuilding*, Michael A. Mullens, Constructability Press, 2011.
- Cantrell, R.A., Nahmens, I., Peavey, J., Bryant, K., Stair, M., *Pre-Disaster Planning for Permanent Housing Recovery, VOLUME 4: Basic Plant Design*, U.S., Department of Housing and Urban Development Office of Policy Development and Research, 2012
- Andrew Gianino, *The Modular Home*, Storey Publishing, 2005
- John Straube, Building America Special Research Project: High R-Value Enclosures for High Performance Residential Buildings in All Climate Zones, Building Science Press, 2010, https://buildingscience.com/sites/default/files/migrate/pdf/BA-1005_High%20R-Value_Walls_Case_Study.pdf

**LEAN manufacturing resource***:*

- Raymond S. Louis, Integrating Kanban with MRPII: Automating a Pull System for Enhanced JIT Inventory Management, Productivity Press
- Ryan E. Smith*, Without A Hitch: New Directions in Prefabricated Architecture, Lean Architecture: Toyota Home Project,* University of Utah, https://scholarworks.umass.edu/wood/2008/

# Appendices

I. Checklist for Factory Start-Up
II. Detailed Conceptual Equipment Costs
III. Building Material List
IV. Detailed Construction Steps Used at Vermod
V. ZEM In-depth Characteristics
VI. Build Timeline
VII. Labor Requirements

## I. Checklist for Factory Start-Up

**Manufacturing requirements (stations, equipment, labor)**

☐ Floor Plan Space sufficient for desired production capacity and factory layout
☐ Factory Floor Plans offer room for expansion through production line re-design, or expansion
☐ Location: within 15 miles from major transportation route
☐ Ceiling Height: at least 24 feet to accommodate cranes and finished housing height
☐ Building structure strong enough to install and operate a crane, or does it need reinforcements
☐ Column spacing: at least 80 linear feet to maneuver work-in-process
☐ Loading docks and garage doors: 20 ft wide doors: at least one for incoming supplies, at least one for outbound modules
☐ Sufficient room for receiving, shipping, material staging, production, office space and break room.

☐ Hydraulic lift or sunken floor to finish the underside of first floor in the factory

☐ Electrical: 1,500-amp for equipment/ tooling (480-volt/240 volt, 3-phase)
☐ Heating equipment to heat the factory
☐ Water, sewer/septic for cleaning and workers
☐ Compressed air with dryer throughout the building
☐ Waste disposal and recycling system
☐ Qualified labor available locally

**ZEM product (operations and sequencing)**

☐ Ability to drywall all exterior walls and ceilings in one station/step, and then drywall soffits and partitions at a later step/station. Or ability to define the air and moisture barrier at a location other than the drywall.
☐ Ability of HVAC installers to install the soffits and the ductwork as one phase of work.
☐ Ability to access below first floor to finish floor
☐ Ability to finish all floors in the factory
☐ Ability to install HVAC in the factory, including ductwork
☐ Access to qualified set crew or GC
☐ Access to reliable vendors of the ZEM components

## II. Detailed Conceptual Equipment Costs

Costs and Quantities adapted from *Pre-Disaster Planning for Permanent Housing Recovery, VOLUME 4: Basic Plant Design*, U.S., Cantrell, R.A., Nahmens, I., Peavey, J., Bryant, K., Stair, M., Department of Housing and Urban Development Office of Policy Development and Research, 2012, and professional experience. The costs presented below assume all new equipment, costs could be reduced by up to 40% by acquiring used equipment from idle or closing plants. Equipment costs will also vary regionally.

| | | Number of Units Needed | | | | Costs Subtotals | | |
|---|---|---|---|---|---|---|---|---|
| | | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** | **Cost per unit** | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** |
| Standard Construction Tools | Floor jig | 2 | 2 | 1 | $9,000 | $18,000 | $18,000 | $9,000 |
| | Sabre saw | 1 | 2 | 9 | $250 | $250 | $500 | $2,250 |
| | Reciprocating saw | 1 | 1 | 4 | $250 | $250 | $250 | $1,000 |
| | Beam Saw | 1 | 1 | 1 | $150 | $150 | $150 | $150 |
| | Table saw | 1 | 2 | 3 | $4,200 | $4,200 | $8,400 | $12,600 |
| | Chop saw | 1 | 1 | 3 | $400 | $400 | $400 | $1,200 |
| | Miter/ radial-arm saw | 1 | 1 | 11 | $450 | $450 | $450 | $4,950 |
| | Wet/tile saw | 0 | 0 | 1 | $300 | $0 | $0 | $300 |
| | Router | 2 | 2 | 8 | $100 | $200 | $200 | $800 |
| | Sander | 1 | 1 | 2 | $400 | $400 | $400 | $800 |
| | Belt Sander | 1 | 1 | 1 | $1,000 | $1,000 | $1,000 | $1,000 |
| | Hot-melt glue system | 0 | 0 | 1 | $3,500 | $0 | $0 | $3,500 |
| | Air compressor pump | 1 | 1 | 2 | $9,000 | $9,000 | $9,000 | $18,000 |

| | | Number of Units Needed | | | | Costs Subtotals | | |
|---|---|---|---|---|---|---|---|---|
| | | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** | **Cost per unit** | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** |
| | Impact wrench | 1 | 1 | 2 | $200 | $200 | $200 | $400 |
| | Metal hand brake | 0 | 0 | 1 | $6,500 | $0 | $0 | $6,500 |
| | Ames mud-tool set | 1 | 1 | 1 | $4,000 | $4,000 | $4,000 | $4,000 |
| | Texture sprayer | 1 | 1 | 1 | $8,000 | $8,000 | $8,000 | $8,000 |
| | Ceiling Spraying equipment | 0 | 0 | 0 | $25,000 | $0 | $0 | $0 |
| | Nail/ brad guns | 4 | 10 | 32 | $250 | $1,000 | $2,500 | $8,000 |
| | Power drill | 4 | 10 | 7 | $100 | $400 | $1,000 | $700 |
| Insulation blowers | Blown-in fibergalss or cellulose machine | 1 | 2 | 1 | $10,000 | $10,000 | $20,000 | $10,000 |
| Carts, ladders, and scaffolding | Lumber cart with flip deck | 0 | 0 | 1 | $21,000 | $0 | $0 | $21,000 |
| | Push Cart | 1 | 1 | 1 | $6,500 | $6,500 | $6,500 | $6,500 |
| | Ladder | 4 | 2 | 4 | $150 | $600 | $300 | $600 |
| | Scaffold | 0 | 1 | 1 | $140,000 | $0 | $140,000 | $140,000 |
| | Safety harness, strap and Cable | 0 | 2 | 2 | $5,500 | $0 | $11,000 | $11,000 |
| Factory automation equipment | Face-framing machine (drill) | 0 | 1 | 1 | $11,500 | $0 | $11,500 | $11,500 |
| | OSB decking monorail | 0 | 0 | 1 | $25,000 | $0 | $0 | $25,000 |

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|  |  | Number of Units Needed |  |  |  | Costs Subtotals |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** | **Cost per unit** | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** |
| Lifting equipment | Diesel forklift (8,000 lbs) | 1 | 1 | 4 | $35,000 | $35,000 | $35,000 | $140,000 |
|  | Hydraulic lifter |  |  | 6 | $9,000 | $0 | $0 | $54,000 |
|  | 1-ton bridge with Crane | 0 | 0 | 1 | $110,000 | $0 | $0 | $110,000 |
|  | 2-ton crane with bridge rails | 0 | 0 | 1 | $120,000 | $0 | $0 | $120,000 |
|  | 4-ton crane with bridge rails | 0 | 1 | 1 | $160,000 | $0 | $160,000 | $160,000 |
| Testing equipment | Di-electric tester | 1 | 2 | 3 | $1,500 | $1,500 | $3,000 | $4,500 |
|  | Circuit continuity tester | 1 | 2 | 8 | $25 | $25 | $50 | $200 |
|  | Breaker test/ torque screwdriver | 1 | 2 | 4 | $250 | $250 | $500 | $1,000 |
|  | Air & water test/ 100-psi pressure gauge | 1 | 2 | 4 | $25 | $25 | $50 | $100 |
|  | Gas tester/ mercury manometer | 1 | 1 | 2 | $90 | $90 | $90 | $180 |
|  | HVAC duct-blaster kit | 0 | 1 | 1 | $1,500 | $0 | $1,500 | $1,500 |
| Delivery equipment | 70’ 30 ton expandable trailers | 5 | 5 | 6 | $50,000 | $250,000 | $250,000 | $300,000 |

|  |  | Number of Units Needed |  |  |  | Costs Subtotals |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** | **Cost per unit** | **Small, crib-build factory** | **Small, line production, low-automation factory** | **Larger, Higher Automation Factory** |
|  | Trucks (pre-owned) | 2 | 2 | 4 | $50,000 | $100,000 | $100,000 | $200,000 |
| **Subtotals** | **Standard Construction Tools** | 24 | 38 | 91 | $77,050 | $47,900 | $54,450 | $83,150 |
|  | **Insulation blowers** | 1 | 2 | 1 | $10,000 | $10,000 | $20,000 | $10,000 |
|  | **Carts, ladders, and scaffolding** | 5 | 6 | 9 | $173,150 | $7,100 | $157,800 | $179,100 |
|  | **Factory automation equipment** | 0 | 1 | 2 | $36,500 | $0 | $11,500 | $36,500 |
|  | **Material handling equipment** | 1 | 2 | 13 | $434,000 | $35,000 | $195,000 | $584,000 |
|  | **Testing equipment** | 5 | 10 | 22 | $3,390 | $1,890 | $5,190 | $7,480 |
|  | **Delivery equipment** | 7 | 7 | 10 | $100,000 | $350,000 | $350,000 | $500,000 |

## III. Building Material List

Below is a partial list of products used at Vermod at the time of the writing of this report, and the Healthy Building Network's (HBN) assessment of the impact of that product on indoor air quality. Vermod is using HBN's recommended "step-up" approach: whenever feasible from a cost and factory process standpoint, Vermod uses an incrementally better, safer, and healthier product. While not all products listed below are highlighted in green, they are often better than the more common alternative.

The first step in sourcing healthy building materials is to understand what products are safe, where safer products exist, and what are the costs and the implications for the workflow of switching to a different product. Factories are also encouraged to buy the product that suits their needs now but write to the distributors or manufacturers advocating for a safer product that still meets their needs.

Hazard spectrum rankings below are an indication of what types of products are typically preferred within a product category based on common content and associated hazards. Product types in green are typically better options than those in orange or red, and product types in yellow are generally less preferable than green, but are better choices than orange or red. The full report is available upon request.

| | **Product** | **Product Type Hazard Spectrum Ranking *** | **Summary Guidance/Alternatives** |
|---|---|---|---|
| **Countertops** | | | |
| | Formica laminate | Plastic Laminate | - Plastic laminate is not a top countertop choice from a health perspective.<br>- Consider higher rated types of countertops like ceramic (made in the USA), solid surface, or engineered quartz.<br>- For continued use of laminate check for availability of ULEF or NAF substrate options.[27] |
| **Flooring** | | | |
| | US Floors Solid Tongue and Groove Traditional Bamboo | Engineered Wood Floors (pre-finished)<br>*Composite wood hazard spectrum:*<br>NAUF | - This flooring is close to the top of our hazard spectrum ranking. Higher rated types of products are Linoleum and Solid Wood Floors (pre-finished).<br>- Consider looking to see if there are bamboo flooring options available with lower formaldehyde emissions.<br>- Prefer mechanical installation over adhesives. |
| | Country Home Collections Luxury Vinyl Tile | Unclear based on available information.<br>Highest possible: New Formulations of Vinyl Floors (phthalate-free)<br>Lowest possible: Traditional Vinyl Floors (with post-consumer recycled content) | - Vinyl floors of any kind are not a preferable material. Higher rated flooring options usable in wet areas include Ceramic Tiles (made in the USA/Lead-free) and Rubber sheet flooring (made without crumb rubber) - both come at a cost premium over vinyl.<br>- If continued use of vinyl is unavoidable, verify with the distributor that there is no recycled content within the product and ask if it is free of orthophthalates. Or look for a different product that is verified to be free of post-consumer/unknown recycled content and free of orthophthalates. |
| **Interior Paint** | | | |

---

[27] No-added formaldehyde (NAF) or ultra-low emitting formaldehyde (ULEF)

| | | | |
|---|---|---|---|
| | Benjamin Moore Ultra Spec 500-eggshell | APE-free, Low VOC Content, and Low VOC Emissions | - This paint product meets most of the targets that HBN has outlined for paint and is good choice of interior paint product.<br>- An improvement would be a paint that is GS-11 certified (Benjamin Moore says this paint meets the requirements of GS-11, but it has not gone through third-party certification to verify this). |
| | Benjamin Moore Ultra Spec Vapor Barrier Primer | Low VOC Content | - Ask Benjamin Moore whether this product is APE-free and if it meets the requirements of the CDPH standard method for testing and evaluating VOC emissions. |
| **Interior Wood Stain** | | | |
| | Zero VOC LENMAR Waterborne Interior Wiping Wood Stain 1WB-1300 | No hazard spectrum | - There does not appear to be a zero VOC version of Lenmar Waterborne interior wiping wood stain.<br>- We don't currently have in-depth research into stains. SCAQMD regulations tend to be some of the most strict (but still achievable) in the country with regard to VOC content. Because of this, we recommend looking for a stain product that, at minimum, meets their requirements. |
| **Insulation** | | | |
| | SIP - BASF Neopor | Estimated: Graphite Polystyrene (GPS) | - Plastic foam insulation in general is not preferred. Within foam there is some polyisocyanurate insulation without halogenated flame retardants which is preferable. We aren't aware of SIPs currently available with this type of insulation. |
| | | | - Many higher-rated insulation products are not conducive to use in SIPs. There does appear to be at least one manufacturer that can provide SIPs using cork insulation, which is high rated, but likely adds a cost premium and a lower R-value than GPS per inch. |
| | Roxul Mineral Wool | Mineral Fiber Batts | - Roxul (now called Rockwool) mineral wool has at least one formaldehyde-free mineral wool batt. We suggest checking to see if this option would work for you. Owens Corning also offers some formaldehyde-free mineral wool batts. |
| **Composite Wood** | | | |
| | Weyerhauser Trus Joists TJIs | Unclear based on available information.<br>Highest possible: ULEF (Ultra-Low Emitting Formaldehyde)<br>Lowest possible: NAUF (no added urea formaldehyde) | - I-Joists are outside of the scope of HomeFree and are not required to meet CARB/TSCA requirements.<br>- Applying the hazard spectrum we developed for interior composite wood products, based on the available information this product is at a minimum NAUF. We recommend asking the manufacturer whether they have emission testing results for their products and what sort of quality controls are in place to ensure the ULEF emission levels are met. |
| | Pacific Woodtech Corp Laminated Veneer Lumber | NAUF (no added urea formaldehyde) | - LVL is outside of the scope of HomeFree and is not required to meet CARB/TSCA requirements.<br>- Applying the hazard spectrum we developed for interior composite wood products, based on the available information this product falls in the NAUF category. We recommending looking for ULEF or NAF options, or using solid wood where possible. |
| | 3/4 OSB ARBEC (sheathing - subfloor) | NAUF (no added urea formaldehyde) | - For interior applications in particular, look for no added formaldehyde products (like those that use only pMDI) or ULEF products with regular test data to ensure consistently low levels of emissions. |
| **Sheathing** | | | |

| | | |
|---|---|---|
| ExoAir 120 + Advantech sheathing *Compared to* Georgia Pacific Forcefield | No hazard spectrum | - Neither option has full content disclosure. We recommend asking for a Health Product Declaration with all content characterized, screened, and identified to at least 1,000 ppm.<br>- Based on the available information, the Forcefield product may be a better option from a health perspective, particularly for occupational concerns since there is nothing to wet-apply at the factory. |
| **Cabinets** | | |
| JS International and Tru Cabinetry | CARB Phase 2 (assumed based on US regulations) | - Legally, any cabinets made in or imported to the US at this point should contain composite wood products that meet CARB requirements. An improvement on this would be to choose products that have solid wood components like doors and drawer fronts, and those that have composite wood products that meet ULEF or NAF requirements. |
| **Interior Doors** | | |
| Brosco (interior) | Not a specific product - general recommendations provided | - Prefer solid wood products over composite (or solid veneers over composite facings).<br>- When using composite wood (for solid core or composite veneer doors), specify materials that are NAF (No Added Formaldehyde) or ULEF (Ultra Low Emitting Formaldehyde) whenever possible. |
| | | - Ask the manufacturer whether the door itself (not just the composite wood components) is free of urea-formaldehyde.<br>- Prefer products that are factory-finished.<br>- Avoid door knobs, hinges, and other hardware advertised as “antimicrobial.” |
| **Decking** | | |
| CCA-Pressure Treated Wood | No hazard spectrum | - CCA (chromated copper arsenate) treated lumber can no longer legally be used for residential decking in the United States, though it is still available for some other applications. **Make sure that you are not actually using CCA treated lumber.**<br>- If possible, prefer wood that doesn’t need to be chemically treated - consider naturally rot-resistant, wood such as cedar, redwood, cypress, or fir. Acetylated lumber also avoids the use of preservatives and appears to be a good option.<br>- Products treated with copper azole and ACQ are better options than arsenic treated products. |
| **Roofing Membrane** | | |
| RPI RE-FLEX EPDM Membrane<br>RPI Royal Edge Bonding Adhesive | No hazard spectrum | - Verify with the manufacturer that this particular EPDM roofing membrane does not contain halogenated or antimony-based flame retardants.<br>- The picture provided shows both the water-based and the low VOC solvent based adhesives. If you don’t need both options for performance reasons, then prefer the water-based adhesive over the “Low VOC solvent-based adhesive.” |
| **Drywall** | | |

| | | | |
|---|---|---|---|
| | National Gypsum or USG Sheetrock Brand Gypsum Panels | No hazard spectrum | - Gypsum panels can contain large quantities of pre-consumer recycled gypsum or FGD - the amount depends on the exact product and manufacture location. Check with USG or National Gypsum on the amount of pre-consumer recycled content in the products you are using.<br>- If possible, avoid pre-consumer recycled content (or prefer products with less) to avoid the release of mercury during manufacturing.<br>- A pilot project has been working on closed loop gypsum recycling of cut off scrap from job sites. If the modular facilities have large quantities of cut off scrap, you may consider trying to participate in a pilot project to recover this material. Read more about the project here. We could connect you with them if interested in learning more about it. |
| | SHEETROCK DURABOND Setting Type Joint Compound and SHEETROCK Brand All Purpose Joint Compound | No hazard spectrum | - To reduce exposure to crystalline silica and other hazardous dust, consider using wet mud (ready-mix) versus dry material, where dust can be generated when mixing with water on site.<br>- The largest exposure potential is likely during sanding operations. Use of wet-sanding techniques cuts down on the creation of dust when drywall mud is sanded - aside from removing the hazardous material, decreasing the amount of dust generated is the most effective protection.<br>- Ask about the source of talc and whether it is verified to be from mines that are not contaminated with asbestos. |
| **Sealants** | | | |
| | Great Stuff Pro Window and Door Insulating Foam Sealant and Todol EZ Flo Gun Foam | One-part polyurethane spray foam sealant | - In general, we recommend the use of the SCAQMD Rule 1168 VOC content limits for sealants.<br>- One-part polyurethane spray foam sealants are not preferred. If a foam sealant is desired, consider those that are not reacted on site, like an expanding polyurethane foam tape.<br>- There are a couple of non-isocyanate spray foam sealants, but due to a lack of disclosure, we are unable to determine whether they are preferred to polyurethane spray foam sealants. If interested in these products, request HPD's. For smaller gaps, look for acrylic-based sealants with very low VOCs - options with ≤ 25 grams per liter (g/L) are available for many applications - making sure it is free of orthophthalate plasticizers. |
| | **Adhesives** | | - |

| | | | |
|---|---|---|---|
| | Dow Great Stuff PRO Wall & Floor Adhesive | Polyurethane | - In general, we recommend the use of the SCAQMD Rule 1168 VOC content limits for adhesives.<br>- Where possible, avoid the use of adhesives altogether by using mechanical installation methods like mechanical fasteners.<br>- Next prefer solid adhesives, like peel-and-stick, to avoid the most hazardous content.<br>- Within wet applied adhesives, prefer acrylic adhesives. Some acrylics may contain orthophthalate plasticizers, though this doesn't appear to be common<br>- -- verify acrylic adhesives you source are free of orthophthalates. |

*Hazard spectrum rankings are based on the most common formulations of product type. Specific product contents can vary considerably within a product type. Individual product contents must be fully disclosed for a robust review and comparison.

## IV. Detailed Construction Steps Used at Vermod:

1. Lay out LVLs – 19oc
2. Set 1st LVL rim and nail on ledger board for TJIs
3. Set TJIs – fasten all together
4. Glue and screw 2nd LVL on outside
5. Square floor framing and install, glue and screw ¾” OSB
6. Lay out outer and inner wall on floor decking
7. Build outer wall on deck
8. Install fabric down center - stapled
9. Install upper sheathing and extend 12” above framing to capture SIPs when installed
10. Frame inner wall on deck
11. Stand walls and set 3” apart
12. 3/4” OSB for top plate to ensure 10” gap
13. Plumb, level and square walls
14. SIP panel installation (4’x14’ panels with TJI embedded on one long axis – glued to next SIP panel
15. Sheetrock tunnel – glue sheetrock to studs
16. Mud and tape sheetrock
17. Install interior walls
18. Rough wire and plumb interior and exterior walls – includes panels and solar rough-in
19. Install interior walls sheetrock
20. Build soffits and sheetrock
21. Mud and tape all sheetrock
22. Install bottom course of exterior sheathing
23. Insulate exterior walls and install last section of sheathing
24. Tape all seams and rough openings
25. Window and door installation
26. Air seal and tape window and doors
27. Build eaves on outside
28. Install fascia and trim work
29. Install rubber membrane roof
30. Install all solar feet and rails and roof
31. Install all siding – metal, vinyl and/or wood
32. Paint inside
33. Install flooring – wood and vinyl
34. Trim out interior – kitchen, bathrooms, lighting, appliances, HVAC and all trim work
35. Jack the house up with hydraulic lifts
36. Finish plumbing, wiring, refrigerant lines
37. Install netting down middle of floor and glue and screw sheathing to TJIs along sides
38. Insulate floor systems
39. Install last section of OSB down middle
40. Tape and seal floor system
41. Lower down on trailer and deliver

## V. ZEM In-depth Characteristics

### Size Specifics of ZEM Housing

When designing ZEM homes, transportation size limits must be kept in mind:

- 12’, 13’, 13’9” are typical width, some manufacturers build to 14’9”, and 15’9” but a police escort is required over 14’, which increases transportation costs, especially over long distances.
- 60’ are typical length of modules, some manufacturers build to 40’ or 70’.
- Module height limit is usually 11’, and is directed by federal, state, and local height limitations. This module height results in the load measuring 13’6” when sitting on top of the carrier, as the carrier is usually 2’6”.

### Foundations

- **Pier foundation**

A pier foundation system is the least expensive option and can reduce the overall foundation costs and installation time by several days. For sites with limited space for excavated material and utilities that run directly under the footprint of the home, piers are a great option to minimize site disturbance.

- **Crawlspace**

**If the house is set on a conditioned crawlspace, the foundation should be properly insulated, air sealed, and built to avoid thermal bridges**

- **Basement**

One of the more expensive options available for a foundation. If a ZEM house is placed on an insulated, conditioned, and ventilated basement, the first floor can be uninsulated.

### First Floor Systems

Homes placed on an insulated, conditioned and ventilated basement can have an uninsulated first floor system. However, if a ZEM home is on an unconditioned space, the floor system must be insulated, air sealed, and made weather-tight in the factory, to maintain the benefits of modular construction. A ZEM home with an insulated floor system requires the following characteristics:

- Minimal thermal bridging;
- No ductwork and plumbing penetrations that would compromise insulation;
- Maximum air tightness through a defined and continuous air barrier; and
- Weather-tight and durable assembly.

Table 8 shows examples of ZEM home floor assemblies that have been used in the Northeast:

**Table 8: First floor assembly options.**

| Structure | Insulation type | Underside Sheathing | R-value |
|---|---|---|---|
| 9.25” TJI, 19" on center (oc)/ Solid Block Bridging | ~9.25” Dense Pack Fiberglass at R4.3/inch | 7/16" OSB with integrated water resistant and air barrier with taped seams on bottom of floor | R-40 |
| 9.25” Open webbed floor joists, 24”oc | ~9.25” Dense Pack Fiberglass | 7/16" OSB with integrated water resistant and air barrier with taped seams on bottom of floor | R-40 |
| 2'' x 12'' Floor Joists - 16''oc/ Solid Block Bridging | • (2) Layers of R-23 Roxul Insulation<br>• Rim Joists @ 1st Floor Floor System with (2) Layers of 2" Rigid Foam | • 7/16" OSB with integrated water resistant and air barrier with taped seams on bottom of floor<br>• Seal Edges with Low Expanding Foam for air sealing | R-46 |
| 2'' x 10'' Floor Joists - 16'' o.c. / Solid Block Bridging | • For conditioned and ventilated basement, so no insulation in the floor | N/A | |

## Exterior Wall

All wall assemblies should incorporate continuous insulation, a well-defined air and weather barrier and a system that manages moisture well. Continuous insulation can be achieved through a variety of approaches including double stud walls, or a single stud wall with exterior continuous insulation, or structural insulated panels (SIPs). In addition, a wide variety of insulation materials can be utilized to achieve the required R-values such as cellulose, mineral wool, wood fiber board, and blown-in fiberglass. In climates of the Northeast, the wall assembly’s air barrier can be defined in several locations including:

- The gypsum wall board through the airtight drywall approach; or
- Exterior sheathing utilizing an OSB with integrated water resistant and air barrier with taped seams.

It is important that the wall assembly is designed to connect with the adjacent assemblies such as the floor or ceiling’s air barrier. This ensures no gaps or penetrations are present at these transitions, so air leakage is prevented. While it’s important to ensure high levels of air tightness and insulation, an exterior wall must also be able to manage moisture. It is important to evaluate the hygrothermal properties of the proposed wall system to prevent moisture from building up in components over time, which can lead to mold and mildew, and structural durability issues over the long term.

Drywall, is typically glued and/or nailed to the studs, rough opening perimeters and top and bottom plates, to achieve greater racking strength and sound-deadening, with all drywall seams landing on the studs and being sealed with tape and joint compound.

Table 9 shows examples of ZEM home wall assemblies that have been used in the Northeast:

**Table 9: Exterior walls assembly options.**

| Structure | Insulation type | Exterior Sheathing | R-value |
|---|---|---|---|
| 10" Exterior Walls. (2) 2x4 Walls Spaced 3" Apart Spaced 3" Apart - 24"oc - 1/2" OSB as Top Plate. | 10" Dense-packed fiberglass insulation at 1.8/lbs per cubic foot, R-value of 4.3/inch | OSB with integrated water resistant and air barrier with taped seams and corners. | R-43 |
| 2x 6 Walls, 24"oc w/ continuous insulation | • Dense Pack Cellulose (R-21)<br>• (1) or (2) 3" polyisocyanurate foam (R-17 each) | OSB with integrated water resistant and air barrier with taped seams | R-38 to R-59 |
| 2x8 stud framing 24"oc<br>2-1/2" @ 24"oc<br>Interior open-built strapping layer for wiring chase | • Dense Pack Cellulose (R33)<br>• 1-9/16" woodfiber exterior sheathing (R-6)<br>• Service cavity can be insulated | 7/16" OSB sheathing | R-39+ |
| 8" SIP | • BASF Neopor graphite infused expanded polystyrene | OSB with integrated water resistant and air barrier with taped seams | R-40 |

## Roofs

### Low Pitch roofs

These are the most typical roofs, and conform to transportation standards. These roofs can be built completely in the factory, while still meeting the size restrictions for transportation.

### Hinged Roof System

In a hinged roof system, each section of the roof is fabricated into two or more components, which are hinged to the module and each other. Hinged roof systems are designed so they lie flat on top of the module during delivery, and once the module is on the foundation, the set crew uses the crane to lift and unfold the roof to its correct height.

### Site-Built Roofs

Another approach often utilized is to have roof trusses or panels delivered to the site for installation in the field. ZEM homes in MMH replacement projects will typically have the roof systems completed at the factory allowing for a turnkey product.

If a steeper pitched roof is desired, the ZEM home can still be delivered with a completed insulated and weather-tight flat roof assembly and roof trusses can be installed on site. A tilt-up, hinged roof assembly can also be integrated into the module in the factory and the roof can be erected on site with a crane and some additional panels to achieve temporary weather-tightness. These site-built roof systems still need to be air sealed, insulated, and made weather-tight on site increasing construction time and cost.

Multiple options are available for the roof system which will be determined by percent completion in the factory, ease of installation (labor hours), cost of components, and roof pitch. If the roof system will incorporate a steeper pitch, it is important to ensure the solar PV system can be oriented within 15 degrees of solar south with the ridge running east to west. It is also important to locate items such as vent pipes, dormers or chimneys on the north side of the roof, or outside of the PV array area.

Some of the roof assemblies that have been used for ZEM homes, in climates of the Northeast, include:

**Table 10: Roof assembly options.**

| **Structure** | **Insulation type** | **R-value** |
|---|---|---|
| Parallel cord truss system, 2x4 top and bottom cords with cross bracing, spaced 24" on center. | Dense-packed with 14" of fiberglass with vented air space below roof deck. | R-60 |
| 12", 4' x 14' SIP panel. TJI joists every four feet that interlock with the opposing panel. | SIP panels with 12" Neopor expanded polystyrene insulation | R-60 |
| Single Pitch, Shed-style Roof System with 9.25" TJIs or 2x10 rafters and continuous insulation | • Dense Pack Cellulose Insulation (R-40)<br>• 4" Polyisocyanurate Rigid Foam installed on the exterior of 5/8" OSB with integrated water resistant and air barrier with taped seams | R-60 |
| Single Pitch, Shed-style Roof System with rafters with continuous insulation | • 9.25" Dense Pack Cellulose Insulation | |
| Common Trusses 24"oc, 2x4 interior strapping @ 24"oc, Siga Majpell Membrane, 5/8" OSB Exterior sheathing | • Dense Pack Cellulose Insulation | R-60 |

*Note: Building roofs as SIP can significantly save on ZEM factory construction time.*

### Windows

ZEM windows also incorporate insulated frames, triple glazing, low-E coatings, and argon gas between panes. There are several manufacturers nationally that provide windows that match these specifications. Some of the specifications that have been used for ZEM homes in the Northeast include U-factors of 0.12-0.21 and solar heat gain coefficient (SHGC) of 0.20-.50.

Another consideration with ZEM homes is passive solar design and ensuring overheating is avoided. When replacing manufactured and mobile homes, often solar orientation is not ideal and can involve the long access of the home running north to south. In this scenario, windows are specified to maximize the insulation value and reduce potential overheating with east and west facing glazing by integrating low SHGC windows. If the home's long access can be oriented east to west, homes can be designed to maximize glazing to the south (for example, 12% glazing to floor area ratio for a climate of the Northeast), and reduce the percentage on the north, east and west glass (for example, 2% glazing to floor area ration in the Northeast). At the same time, the design should consider the use of appropriately sided overhangs to minimize solar gains in the summer and maximize gains in the winter when the sun is lower in the southern sky.

### HVAC and Hot Water

HVAC and domestic hot water equipment that have been successfully factory-installed in ZEM homes, in climates of the Northeast, have included the following components:

- A dedicated mechanical room, located inside the building envelope, housing the water heater, ventilation system, and battery storage. The mechanical room interior walls are insulated with acoustical batts to provide sound dampening.
- Balanced ventilation with heat or energy recovery to provide demand-controlled, and in some cases, conditioned (heated, cooled, and dehumidified air) ventilation through the entire home. Some ventilation systems can monitor $CO_2$ and VOC levels, and operates when specified thresholds are met. The main unit is typically installed in the mechanical room and is ducted throughout the home using 4 & 6 inch ducts located in a soffit chase installed inside the air barrier and thermal envelope. Soffits for the HVAC conduits in ZEM homes are often steel frame to ensure quality and fast installation (wood is often too warped and adds more construction time).
- A ductless cold climate heat pump installed in the main living area (multiple heads for larger homes). This operates in conjunction with the energy recovery ventilation unit and provides primary heating and cooling with the ventilation system mixes the air throughout the home. If installed at the factory, the external compressor must be mounted on the short side of the module, to avoid exceeding the module’s width limitations. The indoor head needs to be installed on the inside of the same short wall as the exterior compressor.
- A heat pump water heater (HPWH) is typically specified, which reduces water heating costs by up to 70% when compared to electric resistance water heating. The HPWH is installed in the mechanical room, and then hot water is delivered throughout the home either directly into adjacent spaces when the mechanical room is close to a kitchen and/or bathroom or routed through the soffit chase inside the thermal envelope.
- The local exhaust and whole house ventilation is provided via the balanced ventilation system. The following average flow rates are achieved and based on the Passive House ventilation standard:
    - Exhaust (continuous)
        - 36 cfm in the kitchen
        - 24 cfm in the bathroom
        - 12 cfm in the powder room / laundry
    - Supply (continuous)
        - ~25 cfm supply per room

## VI. Build Timeline

The time ranges presented in the table below reflect ZEM modular construction on a small scale in a crib factory. If a factory had enough demand for a large volume of ZEM homes and could produce these homes in a highly efficient and automated line production, rather than crib construction, that factory would see significantly shorter production times.

**Table 11: Time to complete key tasks**[28]

| Module construction | Expected range for a ZEM factory |
|---|---|
| Cut to size (Mill) | 80-300 |
| Build floor | |
| Build windows/ door opening subassemblies | |
| Build partition walls | |
| Build side wall | |
| Build end walls | |
| Build marriage wall | |
| Set partition walls | |
| Set exterior and marriage walls | |
| Install rough electric in walls | |
| Air sealing, caulk, foam, tape | 10-30 |
| Build plumbing subassemblies & Install rough plumbing in wall and tubs and roof | 10-50 |
| Build subassemblies for roof | 40-60 |
| Build roof/ceiling | |
| Set roof | |
| Install rough electric in roof | |
| Sheath and install subassembly for roof & Insulate roof | |
| Shingle roof | |
| Prep/drop roof & wrap for shipment | |
| Insulation | 20-60 |
| Install fascia and soffit, Sheath walls, Insulate walls | 10-20 |
| Install windows & exterior doors | 20-25 |
| exterior painting | 10-20 |
| Install siding & trim | 20-40 |
| Hang drywalls on walls | 20-100 |
| Tape & mud drywall | |
| Sand & paint | 20-40 |
| Install cabinet & vanities | 5-10 |
| Fabricate & install kitchen countertops | 5-20 |
| Build finish plumbing subassemblies | 2-10 |
| Install finish plumbing | 2-5 |
| Install finish electric | 3-80 |
| Build interior door subassemblies | 2-10 |
| Install interior doors | 2-10 |
| Install molding | 10-50 |
| Install misc. finish items | 5-10 |
| Install flooring | 5-40 |
| Mechanical/AC | 60-80 |
| Solar | 60-80 |
| Load shiploose | 5-10 |
| Factory touch-up | 10-40 |
| Install plumbing in floor | 5-10 |
| Load module on carrier, Final wrap & prep for shipment, Build major shiploose subassemblies | 2-10 |
| Total factory hours per module | 443-1,220 |

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[28] Based on averages published in Factory Design for Modular Homebuilding, Michael A. Mullens, Constructability Press, 2011, and hourly values provided by Vermod.

# VII. Labor Requirements

**Table 12: Conceptual example of factory labor requirements (Source: adapted from HBN "Unity Homes" business plan)**

| | FTE required by activity | | Trade |
|---|---|---|---|
| | 1 module/day | 2 modules/day | |
| **Mill room** | **1** | **3** | Carpenter and Carpenter helper |
| **Framing** | **4** | **7** | |
| **Rough mechanical** | **4** | **7** | |
| Electrical | 1 | 2 | Carpenter and Carpenter helper |
| Plumbing | 2 | 3 | |
| HVAC | 1 | 2 | |
| **Roof build** | **2** | **4** | Carpenter and Carpenter helper |
| **Shingle or rubber membrane** | **2** | **4** | Roofer |
| **Siding** | **2** | **4** | General construction helper |
| **Inside Finish** | **8** | **13** | General construction helper |
| Floor covering | 1 | 2 | Tile setter or general construction helper |
| Cabinet set | 1 | 2 | Cabinet maker |
| Trim and doors | 1 | 2 | |
| Final clean up | 1 | 2 | General construction helper |
| Material loading and close up | 1 | 1 | |
| Final electrical | 1 | 1 | Electrician and electrician helper |
| Final plumbing | 0 | 1 | Plumber |
| Install HVAC | 2 | 2 | |
| **Drywall finish** | **3** | **5** | Drywall installer, taper, and finisher |
| Back panel hanging | 0 | 1 | Drywall installer |
| Mudding/tape finish | 2 | 3 | Drywall taper |
| Sanding/painting | 1 | 1 | Drywall finisher and painter |
| **Direct construction labor** | **26** | **47** | |
| | | | |
| **Receiving/ material handling** | **1** | **2** | |
| **QA inspection** | **1** | **1** | |
| **Maintenance** | **0** | **1** | |
| **Yard house loader** | **1** | **1** | |
| **General helper labor** | **3** | **5** | |
| | | | |
| **Engineering manager** | **1** | **2** | |
| **Purchasing manager** | **0** | **1** | |

| | FTE required by activity | | Trade |
|---|---|---|---|
| | 1 module/day | 2 modules/day | |
| **Accounts payable and receivable** | **1** | **1** | |
| **Sales/Marketing** | **0** | **1** | |
| **Field Operations Manager** | **0** | **1** | |
| **Total management support staff** | **2** | **6** | |
| | | | |
| **President/ General Manager** | **1** | **1** | |
| **Production/ Plant manager** | **1** | **1** | |
| **Plant line supervisors** | **1** | **2** | |
| **Maintenance supervisor** | **1** | **1** | |
| **HR Director** | **1** | **1** | |
| **CFO/ Controller** | **0** | **1** | |
| **Sales/marketing manager** | **1** | **1** | |
| **Purchasing manager** | **1** | **1** | |
| **QA manager** | **0** | **1** | |
| **Total management staff** | **7** | **10** | |
| | | | |
| **Total operation employment** | **38** | **68** | |

**Table 13: Direct labor rates for New York State**[29]

| Direct Labor Trade Type | Labor Rates |
|---|---|
| Carpenter | $30.11/hr |
| Cabinet maker | $20.00/hr |
| Carpenter helper | $14.93/hr |
| Plumber | $37.49/hr |
| Drywall installer | $28.56/hr |
| Drywall taper | $30.63/hr |
| Electrician | $36.77/hr |
| Electrician helper | $18.00/hr |
| Painter | $16.55/hr |
| Tile setter | $36.28/hr |
| Roofer | $28.94/hr |
| General construction helper | $16.54/hr |
| Truck driver | $23.30/hr |

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[29] Source: Bureau of Labor Statistics, May 2017 State Occupational Employment and Wage Estimates, New York State, mean hourly wage: https://www.bls.gov/oes/current/oessrcst.htm