COMMONWEALTH OF KENTUCKY
BEFORE THE PUBLIC SERVICE COMMISSION

In the Matter of:

Electronic Application Of Kentucky Power Company	)	
For (1) A General Adjustment Of Its Rates For	)	
Electric Service; (2) Approval Of Tariffs And Riders;	)	
(3) Approval Of Accounting Practices To Establish	)	Case No. 2020-00174
Regulatory Assets And Liabilities; (4) Approval Of A	)	
Certificate Of Public Convenience And Necessity;	)	
And (5) All Other Required Approvals And Relief	)	

Joint Intervenors, Mountain Association, Kentuckians for the Commonwealth, and Kentucky Solar Energy Society's Response To Second Set of Data Requests From Commission Staff

Owen Responses – Kentucky 2020-00174

1. Refer to the Direct Testimony of James Owen (Owen Direct Testimony), page 36, lines 7–13.

a. Explain whether Mr. Owen agrees that the dollar-value costs and benefits of distributed energy resources vary by time of day, and, if Mr. Owen does not agree, explain why not.

Answer: Agree.

b. Explain why a net metering credit generated at a certain time of day should be allowed to be used during a different time period. Include in your explanation how allowing this would maintain a price signal for the time-varying costs and benefits of distributed energy resources (DER).

Answer: My testimony in this case was that the Joint Intervenors specifically state their recommendation: "Additionally, the Commission should hold utilities to their full burden of proof and require them to produce substantial evidence for all of the costs and benefits that each solar system contributes to the utility's system." In recommending that the Commission hold Kentucky Power to its burden of proof and require the production of evidence for the costs and benefits of solar, I provided a list of commonly studied benefits and savings due to solar, which many so-called Value-of-Solar studies have examined in jurisdictions across the country. The system-wide benefits or savings experienced due to solar may include: reduced transmission and distribution losses; reduced congestion at stressed nodes and distribution points along the grid; peak load reductions or shifts; reduced costs along the fuel supply line; reduced environmental liabilities and/or environmental compliance costs; avoided generation capacity investments; reduced grid support services; improved grid resiliency; and other system-wide benefits or savings that result from the generation of net-metered solar resources. Without an appropriate value of solar study, the Commission cannot have confidence that the rates charged or netted at certain periods accurately reflect the value the customer-generator adds to the grid. Absent this analysis, customer-generators should not be deprived of netting their production across all usage. In the abstract, I agree that netting across all usage is a blunt instrument. However, in the absence of an appropriate study and data, the Commission cannot discern whether adopting the company's proposed pricing would be a worse price signal for customer-generators who may be providing more benefits to the grid and non-participating customers than they are given credit/ compensated to do.

c. Explain why customers should have the choice to opt-in to the Company's proposed netting periods.

Answer: The company has not met its burden to produce substantial evidence for all of the costs and benefits that each solar system contributes to the utility's system. While it is my primary recommendation that the company's proposal should be rejected, as an alternative, if the Commission intends to allow some part of the proposal to proceed, due to the deficiency in the data, I recommended that the customer-generator have the opportunity

to opt-in to the time-differentiated component of the tariff and those who choose not to opt-in would remain on the existing NMS tariff.

2. Refer to the Owen Direct Testimony, page 37, lines 7–14. Identify and describe specific methodologies for calculating each of the benefits listed in this Testimony.

Answer: I did not conduct analysis to calculate each of the benefits in my testimony. A robust value of solar study would incorporate calculations for each of these components. First, see the 2014 Minnesota value of solar: Methodology (available at https://mn.gov/commerce-stat/pdfs/vos-methodology.pdf). This is an example of a real-world application of a VOS study. Second, I am attaching a recent study titled "A review of the value of solar methodology with a case study of the U.S. VOS". This Study concludes that even when solar owners are provided with a full net metered rate for electricity fed back onto the grid they are subsidizing the electric utility/ other customers. In addition, I would direct the Commission's attention to the best practices in "A Regulator's Guidebook: Calculating the Benefits and Costs of Distributed Solar," available at: http://www.irecusa.org/wp-content/uploads/2013/10/IREC_Rabago_Regulators-Guidebook-to-Assessing-Benefits-and-Costs-of-DSG.pdf; and the "National Standard Practice Manual for Benefit-Cost Assessment of Distributed Energy Resources," available at:

https://www.nationalenergyscreeningproject.org/national-standard-practice-manual/

VERIFICATION

The undersigned, James Owen, being first duly sworn, deposes and says that he has personal knowledge of the matters set forth in the foregoing responses and that the information contained therein is true and correct to the best of his information, knowledge, and belief, after reasonable inquiry.

James Owen

Subscribed and sworn to before me by James Owen this 24 day of February, 2021.

Notary Public

My commission expires: 10/20/2023

ASHLEY NICOLE SUTTERFIELD
Notary Public - Notary Seal
STATE OF MISSOURI
Boone County
My Commission Expires: Oct. 20, 2023
Commission # 19546667

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A review of the value of solar methodology with a case study of the U. S. VOS

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ABSTRACT

Distributed generation with solar photovoltaic (PV) technology is economically competitive if net metered in the U.S. Yet there is evidence that net metering is misrepresenting the true value of distributed solar generation so that the value of solar (VOS) is becoming the preferred method for evaluating economics of grid-tied PV. VOS calculations are challenging and there is widespread disagreement in the literature on the methods and data needed. To overcome these limitations, this study reviews past VOS studies to develop a generalized model that considers realistic future avoided costs and liabilities. The approach used here is bottom-up modeling where the final VOS for a utility system is calculated. The avoided costs considered are: plant O&M fixed and variable; fuel; generation capacity, reserve capacity, transmission capacity, distribution capacity, and environmental and health liability. The VOS represents the sum of these avoided costs. Each sub-component of the VOS has a sensitivity analysis run on the core variables and these sensitivities are applied for the total VOS. The results show that grid-tied utility customers are being grossly under-compensated in most of the U.S. as the value of solar eclipses the net metering rate as well as two-tiered rates. It can be concluded that substantial future work is needed for regulatory reform to ensure that grid-tied solar PV owners are not unjustly subsidizing U.S. electric utilities.

1. Introduction

Solar photovoltaic (PV) technologies have had a rapid industrial learning curve [1–4], which has resulted in continuous cost reductions and improved economics [5,6]. This constant cost reduction pressure has resulted in a spot price of polysilicon Chinese-manufactured PV modules of only US$0.18/W as of April 2020 [7]. There are several technical improvements, which are both already available and slated to drive the costs further down such as black silicon [8–10]. The International Renewable Energy Agency (IRENA) can thus confidently predict that PV prices will fall by another 60% in the next decade [11]. However, even at current prices, any scale of PV provides a levelized cost of electricity (LCOE) [12] lower than the net metered cost of grid electricity [13] and this will only improve with storage costs declining [14–18]. Specifically, PV already provides a lower levelized cost of electricity [12,19,20] than coal-fired electricity [13,21,22]. In addition, PV technology can be inherently distributed (e.g. each electricity consumer produces some or all of their electricity on site thus becoming 'prosumers'). Distributed generation with PV has several technical advantages, including improved reliability, reduced transmission losses [23,24], enhanced voltage profile, reduced transmission and distribution losses [25], transmission and distribution infrastructures deferment, and enhanced power quality [26]. As PV prices decline, prices of conventional fossil fuel-based electricity production are increasing due to aging infrastructure [27–29], increased regulations (in some jurisdictions) [30–33], fossil fuel scarcity [34–36], and pollution costs [37–41]. Thus, PV represents a threat to conventional utility business models [42] and there is evidence that some utilities are manipulating rates to discourage distributed generation with solar [43], while others are embracing it such as Austin Texas or the state of Minnesota [44]. Rates structures vary widely throughout the U.S [45–48]. and there has been significant effort to determine the actual value of solar (VOS) electricity.

This shift towards VOS is fueled by criticisms of its predecessor [49], net metering, that is misrepresenting the true value of distributed solar generation [50–52]. VOS is more representative of the electricity cost because under a Value of Solar Tariff (VOST) scheme, the utility purchases part of, or the whole net solar photovoltaic electricity generation from its customers, therefore dissociating the VOST from the electricity

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Nomenclature:

B	Burner tip fuel price [$/MMBtu]
C_D	Distribution capacity [MW]
C_G	Utility generation capacity [p.u.]
C_H	Health cost of natural gas [$/kWh]
C_{PV}	PV capacity for year 'n' [kW]
C_T	Transmission capacity [p.u.]
D	Utility Discount rate
D_E	Environmental discount rate
D_H	Heat rate degradation rate
D_{PV}	Degradation rate of PV
E	Environmental cost [$/MMBtu]
F	Utility discount factor
F_E	Environmental discount factor
h	Number of hours in the analysis period
H_C	Heat rate of combined cycle gas turbine [Btu/kWh]
H_{CT}	Heat rate of peaker combustion turbine [Btu/kWh]
H_n	Heat rate for year n [Btu/kWh]
H_P	Heat rate of the plant [Btu/kWh]
H_S	Solar heat rate [Btu/kWh]
i	Number of years in analysis period
I_C	Installation cost of combined cycle gas turbine [$/kW]
I_D	Investment on distribution capacity per year without PV [$]
I_{DP}	Investment on distribution capacity per year with PV [$]
I_P	Installation cost of peaker combustion turbine [$/kW]
K	Growth rate
M	Reserve capacity margin
n	nth year of analysis period
O	Output of the PV [kWh]
$PL1$	1st year load capacity [kW]
$PL10$	10th year load capacity [kW]
Q	Distribution cost [$/kW]
S	PV fleet shape [kW]
S_C	Solar capacity cost [$/kW]
U_C	Utility cost [$]
U_F	Utility fixed operation and maintenance cost [$/kW]
U_P	Utility price [$/kWh]
U_T	Utility transmission capacity cost [$/kW]
U_V	Utility variables operation and maintenance cost [$/kWh]
VOS	Value of solar [$/kWh]
V_x	V_1: Avoided operation and maintenance fixed cost [$]$V_2$: Avoided operation and maintenance variable cost [$]$V_3$: Avoided fuel cost [$]V_4: Avoided generation capacity cost [$]$V_5$: Avoided reserve Capacity cost [$]$V_6$: Avoided transmission capacity cost [$]$V_7$: Avoided distribution cost [$]$V_8$: Avoided environmental cost [$]$V_9$: Avoided health liability [$]

retail price [51,53]. Performing a complete VOS calculation, however, is challenging. One of the main challenges is data availability and accuracy [54,55]. Three data challenges have been identified by Ref. [55] that are: 1) the time granularity of the solar irradiation data, 2) the origin of the data, modeled versus measured, and 3) the data measurement accuracy. Other challenges faced by utilities while assessing the VOS are which components to include in the calculations, and what calculations method to assess the value of each components [56]. The possible components across the literature that are suggested to be included in a VOS as avoided costs and solar benefits are: **energy production costs** (operation and maintenance) [45–47,57–63], **electricity generation capacity costs** [45–47,50,57–63], **transmission capacity costs** [45–47,50,57–61,63], **distribution capacity costs** [45–47,50,57–63], **fuel costs** [45–47,50,57,60–63], **environmental costs** [45,47,57,58,60–63], **ancillary including voltage control benefits** [47,57–59,63], **solar integration costs** [47], **market price reduction benefits** [47,60], **economic development value or job creation** [46,47,57,60,61], **health liability costs** [57,60,64]**,** and **value of increased security** [47,57]. A guidebook has been developed by the United States' Interstate Renewable Energy Council (IREC) for the calculation of several of the VOS components [57]. These methods have been further developed by the U.S. National Renewable Energy Laboratory (NREL) [58]. NREL has provided more detailed calculation methods than the guidebook from the IREC with a different level of accuracy. The methods with a higher level of accuracy are more complicated to implement and require a higher level of data granularity. A qualitative study on VOS performed in 2014 suggested the inclusion of all relevant components in a VOS studies [64]. The calculation of the VOS can be done annually, as in the case of Austin Energy [50,53], or can be fixed for a selected period, as per the case of Minnesota state's VOS (25 years) [45,53]. There are recently an increasing number of studies looking into externality-based components of VOS especially environmental costs and health liability costs [65–67]. This is because a country with high solar PV penetration rate provides a healthy population according to a German study [68]. An estimated average of 1424 lives could be saved each summer in the Eastern United States, and $13.1 billion in terms of health savings if the total electricity generation capacity in the Eastern United States included 17% of solar PV [69]. For the entire U.S. if coal-fired electricity were replaced with solar generation, roughly 52,000 premature American deaths would be prevented from reduced air pollution alone [70]. Not surprisingly, the latest report from North Carolina Clean Energy Technology Center found out that there are policy changes on VOS across the United States with 46 states, in addition of DC considering making significant changes in their solar policies and might be transitioning to a VOS model in coming years [63].

This indicates VOS is the way of the future for grid integrated PV, but how exactly should solar be valued on the modern grid? In this study the VOS literature is reviewed, and a generalized model is developed taking realistic future avoided costs and liabilities into account from the literature. The approach used here is a bottom-up modeling where the final value of solar to a utility system is calculated. This model factors in the existing parameters, that have been identified in VOS studies in different U.S. jurisdictions. The approach starts from the existing formula to calculate the levelized cost of electricity from solar PV technology [12] and updates the formula by adding the avoided and opportunity costs and the effect of different externalities. The costs considered in the study are: avoided plant operation and maintenance (O&M) fixed cost; avoided O&M variable cost; avoided fuel cost; avoided generation capacity cost, avoided reserve capacity cost, avoided transmission capacity cost, avoided distribution capacity cost, avoided environmental cost, and the avoided health liability cost. The value of solar represents the sum of these costs. Each sub-component of the VOS has a sensitivity analysis run on the core variables and these sensitivities are applied for the total VOS. These sensitivities are limited by the best available data on the variables in the literature and future work is needed to quantify the secondary costs that would lead to an even higher VOS. The conservative results developed here are presented and discussed in the context of aligning policy and regulations with appropriate compensation for PV-asset owners and electric utility customers.

2. Methods/theory

2.1. Avoided plant O&M – fixed cost (V_1)

The use of solar energy results in a displacement of energy production from conventional energy sources. The avoided cost of plant operation and maintenance (V_1) [$] depends on the energy saved by using solar PV for electricity generation instead of conventional energy generation processes. Equation (1) describes the calculation of the capacity of solar PV (C_{PV}) [kW] throughout the lifetime of the solar PV system. During the first year of operation, the installed solar PV system is considered to not have suffered any degradation. Therefore, the capacity has a value of one. The degradation of the installed solar PV system is expressed by the degradation rate of PV (D_{PV}) and for a marginal year (n), the marginal capacity of the installed PV system for that year would be:

$$C_{PV} = (1 - D_{PV})^n \quad (1)$$

The fixed O&M cost is directly linked to the need for new conventional electricity generation plants. If the construction of new conventional generators in the location of interest can be avoided, there is no need to include the fixed O&M in the valuation of solar for this location. To calculate the value of the fixed O&M (V_1), the value of the utility cost (U_C) [$] needs to be known first. The utility cost depends on four parameters, the capacity of solar PV (C_{PV}) mentioned above, the utility capacity (C_G) [p.u.], the utility fixed O&M cost (U_F) [$/kW], and the utility discount factor (F). To calculate this utility cost, first the ratio of the capacity of solar to the utility capacity is calculated. This ratio is then multiplied by the utility fixed O&M cost. A discount is applied to the result by multiplying it by the utility discount factor [71]. The discount factor (F) depends on the year and can be calculated by using the discount rate (D). The discount factor for year (n) is [45]:

$$F = \frac{1}{(1 + D)^n} \quad (2)$$

The discount rate used in the formula describes the uncertainty and the fluctuation of the value of money in time. The value of the discount rate differs when considered from a utility point of view or a societal point of view and can highly impact the utility cost. While considering the economics of solar PV systems [57], has suggested the use of a discount rate lower than the value used by the utility.

$$U_C = U_F * \frac{C_{PV}}{C_G} * F \quad (3)$$

The avoided plant O&M fixed cost (V_1) is then calculated by summing the utility cost for all the years included in the analysis period.

$$V_1 = \sum\nolimits_0^i U_C \quad (4)$$

2.2. Avoided plant O&M – variable cost (V_2)

The utility cost for the avoided variable O&M cost (V_2) [$] is calculated by multiplying the utility variable O&M cost (U_V) [$/kWh] by the energy saved by using solar PV systems or the output of the solar PV system (O) [kWh], and the result is discounted by the discount factor (F).

$$U_C = U_V * O * F \quad (5)$$

The avoided variable O&M (V_2) cost is the sum of the utility cost over the analysis period:

$$V_2 = \sum\nolimits_0^i U_C \quad (6)$$

2.3. Avoided fuel cost (V_3)

Additionally, the calculation of the utility price (U_P) [$/kWh] require the knowledge of the equivalent heat rate of a marginal solar. According to Ref. [72], the heat rate [Btu/kWh] describes how much fuel-energy, on average, a generator uses in order to produce 1 kWh of electricity. It is typically used in the energy calculation of thermal-based plants and is therefore misleading for the calculation of solar energy production. Since the method evaluates the avoided cost from thermal-based plants, however, it is applied to solar PV generation. The heat rate (H_S) [Btu/kWh] of solar PV or displaced fuel heat rate during the first marginal year is calculated as:

$$H_S = \frac{\sum_0^h (H_p * S)}{\sum_0^h S} \quad (7)$$

In the equation above, the heat rate (H_p) [Btu/kWh] represent the real value of the utility plant's heat rate during the operation hours of the solar PV systems over the analysis period and the parameter (S) [kW] describes the PV fleet shape that is the hourly PV fleet shape production over the hours (h) in the analysis period.

After the heat rate for the first year has been calculated, the heat rate for the succeeding years in the analysis period can be calculated by the following equation [45]:

$$H_n = H_S * (1 - D_H)^n \quad (8)$$

The primary use of heat rates is the assessment of the thermal conversion efficiency of fuel into electricity by conventional power plants. As a result, it is natural to deduce that the rate at which the heat rate (D_H) decreases corresponds to the efficiency lost rate of the power plant [73].

The utility price (U_P) depends on the heat rates and can be calculated once the heat rate is known as:

$$U_P = \frac{B * H_n}{10^6} \quad (9)$$

Another parameter to account for is the burner tip price (B) [$/MMBtu]. The burner tip price describes the cost of burning fuel to create heat in any fuel-burning equipment [74].

The avoided fuel cost (V_3) [$] is calculated in a similar way as the value of the fixed O&M. First, the utility cost is calculated by multiplying the value of the per unit PV output (O) by the utility price (U_P). The result is then discounted by the discount factor. The discount factor used in the case of the avoided fuel cost depends on the treasury yield [45]. The avoided fuel cost is obtained by summing up the utility cost over the analysis period.

$$U_C = U_P * O * F \quad (10)$$

$$V_3 = \sum\nolimits_0^i U_C \quad (11)$$

2.4. Avoided generation capacity cost (V_4)

The installation of solar systems reduces the generation of electricity from new plants. This is represented by the avoided capacity cost. To calculate the avoided generation capacity cost, the solar capacity cost (S_C) [$/kW] needs to be known. Two variables are essential to evaluate the solar capacity cost, the cost of peaker combustion turbine (I_P) [$/kW] and the installed capital cost (I_C) [$/kW]. The cost of peaker combustion turbine (I_P) is the cost associated with the operation of a turbine that function only when the electricity demand is at its highest. The installed capital cost (I_C) describes the cost of combined cycle gas turbine updated by the cost based on the heat rate. The solar capacity can be calculated as follows [75]:

$$S_C = I_C + (H_S - H_C) * \frac{I_P - I_C}{H_{CT} - H_C} \quad (12)$$

H_{CT} [Btu/kWh] and H_C [Btu/kWh] are respectively the heat rate of the peaker combustion turbine, and the combined cycle gas turbine. After the calculation of the solar capacity cost (S_C), the utility cost can be obtained by first, multiplying the ratio of solar PV capacity (C_{PV}) and utility generation capacity (C_G) by the value of solar capacity cost (S_C). Then, the result is discounted by the discount factor (F) to obtain the final value of the utility cost. And as in the previous cases the value of avoided generation capacity is the sum of the utility cost overs the analysis period.

$$U_C = S_C * \frac{C_{PV}}{C_G} * F \tag{13}$$

$$V_4 = \sum_0^i U_C \tag{14}$$

2.5. Avoided reserve capacity cost (V_5)

The calculation of the avoided reserve capacity cost (V_4) [$] follows the same pattern as the avoided cost of generation capacity. But in this case, the effective solar capacity, that is the ratio of the solar PV capacity (C_{PV}) and utility generation capacity (C_G) is multiply by the solar capacity cost, then the result is multiplied by the reserve capacity margin (M) to obtain the utility costs. After that, the utility cost is discounted as previously described by the discount factor (F). Then, the avoided reserve capacity is calculated by adding up the utility cost over the analysis period [58].

$$U_C = S_C * \frac{C_{PV}}{C_G} * M * F \tag{15}$$

$$V_5 = \sum_0^i U_C \tag{16}$$

2.6. Avoided transmission capacity cost (V_6)

The avoided transmission capacity cost (V_6) [$] calculation is also performed similarly to the avoided generation capacity cost. This cost describes the losses that are avoided when electricity does not have to be transported on long distance because of installed solar systems. It is calculated by first multiplying the utility transmission capacity cost (U_T) [$/kW] by the solar PV capacity (C_{PV}). The result is then divided by the transmission capacity (C_T) [p.u.] and the discount factor (F) is applied to obtain the utility cost for a marginal year. The avoided transmission cost is calculated by the sum, over the years in the analysis period, of the corresponding utility costs [76].

$$U_C = U_T * \frac{C_{PV}}{C_T} * F \tag{17}$$

$$V_6 = \sum_0^i U_C \tag{18}$$

2.7. Avoided distribution capacity cost (V_7)

The two major variables that influence the avoided distribution capacity cost (V_7) [$] are the peak growth rate (K) and the system wide costs. The system wide costs account for several financial aspects of a distribution plant, among which, overhead lines and devices, underground cables, line transformers, leased property, streetlights, poles, towers etc. [77].

All the deferrable system wide costs throughout a year have been summed up and the result divided by the yearly peak load increase in kW over a total period of a decade to obtain the distribution cost per growth of demand.

The ratio of the 10th year peak load (PL_{10}) [kW] and the 1st year peak load (PL1) [kW] are used in the calculation of the growth rate (K) of demand. The expression of the growth rate (K) is as follows [45,78]:

$$K = \left(\frac{PL_{10}}{PL_1}\right)^{\frac{1}{10}} - 1 \tag{19}$$

The distribution capital cost (Q) [$/kW] is utility owned data and depends on the utility, and the growth rate (K) that can be obtained by using the previous formula. An escalation factor is necessary to evaluate the distribution cost for deferral consecutive years [79].

After obtaining the distribution cost (Q) from the utility and growth rate (K) calculated, the distribution capacity (C_D) [kW] can be calculated from the growth rate. The result is then multiplied by the distribution cost and discounted by the discount factor (F) to get the discounted cost for a particular year. The discounted cost for the analysis period can in turn be used to calculate the investment during each year (I_D) [$] of the analysis period [45].

$$I_D = C_D * Q * F \tag{20}$$

When there is no other generation system than solar PV that comprised the installed capacity, the investment per year (I_{DP}) [$] in terms of deferred distribution can be calculated from the investment deferred [45].

$$I_{DP} = C_D * Q * DF \quad \text{(in terms of deferred distribution)} \tag{21}$$

After obtaining the yearly investment without PV (I_D) and the yearly investment in terms of deferred distribution (I_{DP}), the utility cost can be obtained by dividing the difference between the yearly investment without PV and the yearly investment with PV by the distribution capacity (C_D). This utility cost can be called the deferred cost per kW of solar. This deferred cost per kW of solar is discounted by the discount factor (F), multiplied by the solar PV capacity, and summed up over the analysis period to obtain the avoided distribution capacity cost.

$$U_C = \frac{I_D - I_{DP}}{C_D} * F * C_{PV} \tag{22}$$

$$V_7 = \sum_0^i U_C \tag{23}$$

2.8. Avoided environmental cost (V_8)

The three major pollutants that are considered in the calculation of the avoided environmental cost (V8) [$] are: greenhouse gases (GHGs), pollutants sulfur dioxide, nitrogen oxide, and hazardous particulates [80].

The two parameters that influences the cost linked to CO_2 and other greenhouse gasses' emission are the social cost of CO_2 and the gas emission factor [81]. With these two variables, the cost of avoided CO_2 can be calculated in dollars and then the real value linked to this cost is obtained by converting the previously calculated value in current value of dollars. This is done by multiplying the externality cost of CO_2 by the consumer price index (CPI) [82]. The obtained result is then multiplied by the general escalation rate for the following years [80]. The cost of CO_2 for every year is obtained by multiplying the previous value by pounds of CO_2 per kWh. The same logic is applied to the other pollutants to calculate the related costs and the cost related to all three categories of pollutant are added up to get the environmental cost (E) [$/MMBtu].

By multiplying the environmental cost by the solar heat rate (H_S), the utility cost (U_C) is obtained. An environmental discount factor (F_E) is applied to the utility factor. The environmental discount factor (F_E) is defined as follows [83]:

$$F_E = \frac{1}{(1 + D_E)^n} \tag{24}$$

Here, D_E is the environmental discount rate taken from the Social Cost of Carbon report [81].

$$U_C = E * H_S * F_E * O \tag{25}$$

$$V_8 = \sum_0^i U_C \tag{26}$$

2.9. Avoided health liability cost (V_9)

The use of solar PV systems prevents part of the emissions of pollutants from getting into the air. This can in turn result in great health benefits. The harmful pollutants that greatly impact human health are NO_x and SO_2. These two chemicals react with other compounds when they are released in the air to form a heavy and harmful product that is called particulate matter $PM_{2.5,}$ [84–86]. Particulate matter $PM_{2.5,}$ can cause diseases such as lung cancer and cardiopulmonary diseases [87]. It is difficult to evaluate the cost related to the avoided health liabilities and the saved lives. Several works have investigated the calculation of the cost of human health related to electricity production through fossil fuels [88–91]. Nevertheless, the most relevant approach is the work of [91] because the methods accounts for changes of the cost at a regional and plant level. This has been made possible because of data collected by EPA on the emission level of facilities through the Clean Air Markets Program. The result obtained by Ref. [91] is conservative as it does not include environmental impacts over the long term (e.g. climate change) [66,68,69,92]. The calculation of the cost of health liability by Ref. [91] depends on the quantity of pollutants emitted [tons/year] during a year, the cost of a unit mass of emission for each pollutant in [$/tons], and the annual gross load [kWh/year].

The health cost of energy produced by fossil fuel sources (C_H) [$/kWh] obtained by Ref. [91] are used to calculate the utility cost. The utility cost (U_C) is the product of the health cost by the PV systems output (O), that is discounted by the environmental discount factor (F_E).

$$U_C = C_H * O * F_E \tag{27}$$

The avoided health liability cost (V_9) [$] is then calculated by:

$$V_9 = \sum\nolimits_0^i U_C \tag{28}$$

2.10. Value of solar (VOS)

There are three different ways to represent the value of solar. It can be expressed either as the annual cost [$] over the analysis period or the lifetime of the installed solar photovoltaic system, or as the cost per unit of solar PV power installed [$/kW], or finally as the cost of generated electricity by the solar system [$/kWh] [58]. The most commonly used metric to express the VOS is the cost of electricity generated by the solar system [$/kWh] because it is user friendly and is the same metric used by utilities on electricity bills [58]. To calculate the levelized value of VOS per kilowatt-hour of electricity produced, the sum of the value of all the avoided cost is calculated and then divided by the total amount of energy produced (O) during the analysis period discounted by the discount factor (F).

$$VOS = \frac{V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9}{\sum_0^i (O * F)} \tag{29}$$

where:

V_1: Avoided O&M fixed cost.
V_2: Avoided O&M variable cost.
V_2: Avoided fuel cost.
V_4: Avoided generation capacity cost.
V_5: Avoided reserve capacity cost.
V_6: Avoided transmission capacity cost.
V_7: Avoided distribution cost.
V_8: Avoided environmental cost.
V_9: Avoided health liability cost.
O: Output of the solar PV system.
F: Utility discount factor.

3. Sensitivity

The calculation of VOS requires several parameters that come from different sources. Some parameters are location dependent, while other parameters are state dependent, and there are parameters that are utility dependent. Many of these parameters can also change from one year to another. As a result, there are wide differences in the calculation of VOS across the literature [56]. The utility-related parameters that can change from one VOS calculation to another are the number of years in the analysis period (i), the utility discount rate (D), the utility degradation rate, the utility O&M fixed, and variable costs, the O&M cost escalation rate, the hourly heat rate (H_P), the heat rate degradation rate (D_H), the reserve capacity margin (M), the transmission capacity cost (U_T), the peak load of year 1 (PL_1) and year 10 (PL_{10}), the distribution cost (Q), the distribution cost escalation factor (G_D), and the distribution capacity (C_D). Parameters such as the cost of peaker combustion turbine (I_P), the cost of combine cycle gas turbine (I_C), the heat rate of peaker combustion turbine (H_{CT}), and the heat rate of combine cycle gas turbine (H_C) can be either obtained from the utility or from the U.S. Energy Information Agency. The solar PV fleet (S) can also be obtained from the utility or by simulation using the open source Solar Advisory Model (SAM) (https://github.com/NREL/SAM) [45]. Other variables that can affect the VOS but are not controlled by the utility are the PV degradation rate (D_{PV}), the environmental discount factor (F_E), the environmental cost of conventional energy, the health cost of conventional energy, and the cost of natural gas on the energy market. Table 1 summarizes high and low estimates of the values for the variables that are required to perform a VOS calculation and the VOS component they are used to calculate.

3.1. Number of years in analysis period

The number of years in the analysis period varies and can be as low as 20 years, and as high as 30 years or more [12,57]. The typical warranty provided by solar panels manufacturer is 25 years. As a result, it is reasonable to set the lowest value of the analysis period to 25 years. Also, solar modules have proved to continue to reliably deliver energy 30 years after the installation of the system [57], therefore, 30 years has been set as the higher value of the analysis period in this study. Keyes et al. have pointed out that utility planning is often over shorter time periods (e.g. 10–20 years) [57]. However, economic decisions should be made over the entire life of the physical project not an arbitrary cutoff date [102] and there are existing methods to estimate the load growth on the utility side as it is usually done for conventional energy generators [53].

3.2. PV system degradation rate

The degradation rate of PV panels overtime depends on the location of operation as well as climate conditions (temperature, wind speed, dust, etc.). A statistical study conducted by the National Renewable Energy Laboratory [93] has found the value of the PV system degradation rate to be comprised between 0.5% and 1%. These two values are the boundaries that will be used as low and high values for the sensitivity analysis on the PV system degradation rate.

3.3. Utility discount rate

The discount rate is used to assess the change in money value overtime. This value can change depending not only on the location, but also, on the utility. A discount rate value as high as 9% can be used or a value as low as the inflation rate might be used. The discount rate used by utilities are usually in the high values, but the social discount rate is closer to the inflation rate [57]. As a result, 9% will be considered as the high-end value of the discount rate while the current inflation rate of 2.18% will be considered for the lowest value. It is important to note that the value of the inflation rate changes with time and if this value is chosen as the discount rate it should be updated regularly for new calculations of the VOS. Also, the value of the inflation rate can be subjected to ongoing events. The value of the inflation rate of 2.18% was chosen at a date before the coronavirus outbreak in the United States that is ongoing. The outbreak has brought the inflation rate to as low as

Table 1
Assumptions used for required variables for a VOS calculation.

Variable	High estimate	Source	Low estimate	Source	VOS components
Degradation rate of PV (D_{PV}) [%]	1	[93]	0.5	[57,93,94]	All components
Distribution capacity (C_D) [kW]	429,000	[95]	237,000	[95]	Avoided distribution cost (V_7)
Distribution cost (Q) [$/kW]	1104	[95]	678	[95]	Avoided distribution cost (V_7)
Environment discount rate (D_E) [%]	2.5	[81]	5	[81]	Avoided environmental cost (V_8)
Environmental Cost (E) [$/metric tons of CO_2]	[62–89]	[81]	[12–23]	[81]	Avoided environmental cost (V_8)
Health cost of natural gas (C_H)[$/kWh]	0.025	[91]	0.025	[91]	Avoided health liability cost (V_9)
Heat rate degradation rate (D_H) [%]	0.2	[96]	0.05	[96]	•Avoided fuel cost (V_3) •Avoided environmental cost (V_8)
Heat rate of combined cycle gas (H_C) [Btu/kWh]	7627	[97]			•Avoided generation capacity cost (V_4) •Avoided reserve capacity cost (V_5)
Heat rate of peaker combustion turbine (H_{CT}) [Btu/kWh]	11,138	[97]			•Avoided generation capacity cost (V_4) •Avoided reserve capacity cost (V_5)
Installation capital cost of combined cycle gas turbine (I_C) [$/kW]	896	[98]			•Avoided generation capacity cost (V_4) •Avoided reserve capacity cost (V_5)
Installation cost of peaker combustion turbine (I_P) [$/kW]	1496	[98]			•Avoided generation capacity cost (V_4) •Avoided reserve capacity cost (V_5)
Load Growth Rate (K) [%]	1.17	[99]	−0.94	[99]	Avoided distribution capacity cost (V_7)
Number of years in analysis period	30	[57]	25	PV industry warranties	All components
Reserve capacity margin (M) [%]	36	[100]	13	[100]	Avoided reserve capacity (V_5)
Solar Heat Rate (H_S) [Btu/kWh]	8000	[53]			•Avoided fuel cost (V_3) •Avoided generation capacity cost (V_4) •Avoided reserve capacity cost (V_5) •Avoided environmental cost (V_8)
Transmission capacity cost (U_T) [$/kW]	130.535	[101]	17.895	[101]	Avoided transmission capacity (V_6)
Utility Discount rate (D) [%]	9	[57]	2.18	[57]	•Avoided plants O&M fixed cost (V_1) •Avoided plants O&M variable (V_2) •Avoided generation capacity cost (V_4) •Avoided reserve capacity cost (V_5) •Avoided transmission capacity cost (V_6) •Avoided distribution capacity cost (V_7)
Utility fixed O&M cost (U_F) [$/kW]	18.86	[95]	7.44	[95]	Avoided O&M fixed cost (V_1)
Utility variable O&M cost (U_V) [$/kWh]	0.01153	[95]	0.00216	[95]	Avoided O&M variable cost (V_2)

0.25%. This value will not be used to run a sensitivity analysis because of the special conditions in which it occurred.

3.4. Environmental cost

The environmental cost associated with electricity production through conventional energy sources depends on the cost associated with the pollution from carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x), and hazardous particulates (PM). The environmental cost of carbon dioxide dominates the cost of the other components. Different estimates of the CO_2 cost are given by the EPA [81]. The cost of CO, NO_x, and PM depends on state laws. The lowest value and highest value used for the cost of CO, NO_x, and PM were chosen from the state of Minnesota [103]. It has been hypothesized that if conventional energy sources are being used to produce electricity in the future, the effects on environment are going to worsen (e.g. lower quality fuel, higher embodied energies, etc.), therefore the environmental cost will be expected to increase. This will be investigated by raising the environmental cost while analyzing the sensitivity of VOS to the environmental cost. This will show the trend of the impact of the environmental cost on the VOS and in the future, the values will need to be updated because the environmental cost is likely to exceed the maximum used value in this study.

3.5. Health liability cost

The health liability cost is a new calculated VOS component introduced by this study. This component has been mentioned by several studies but was not incorporated in the calculation due to lack of data for the evaluation [57,66,67,104]. The health and mortality impacts of coal in particular are so severe an ethical case can be made for the industries elimination [105]. For example, Burney estimated that 26,610 American lives were saved between 2005 and 2016 by a conversion of coal-fired units to natural gas in the U.S [106]. More lives as well as non-lethal health impacts would be avoided with a greater transition from coal to solar [70]. The values used here were obtained from the study of [91] that found the value of health impact cost of natural gas to be $0.025/kWh. As previously hypothesized, the use of fossil fuel energy sources in the future will increase the emissions, and the cost of health care has been escalating faster than inflation [106] thus increasing the cost of derived health liability. Several increase rates will be investigated. Although it should be pointed out the approach taken here was extremely conservative as the potential for climate/greenhouse gas emission liability [107,108] was left for future work as discussed below.

3.6. Other parameters

The other parameters are utility related and in case of absence of utility data, generic values from the U.S. government agencies is used as indicated in Table 1 and run through realistic percent increases or decreases to determine their effect on the VOS components.

3.7. Sensitivity analysis

A sensitivity analysis has been run on each of the nine VOS components as well as on the VOS. For each component, the sensitivity has been analyzed for some of its parameters wherever data was available. The evaluation of the variability of the VOS components has been performed for each parameter. The sensitivity of a component to one of its parameters is determined by maintaining an average value of the other parameters and varying the studied parameter from its lowest value to its highest value. The different values that are obtained for the VOS component are then plotted to show its variation according to the parameter studied. A correlation study between the different parameters has not been conducted because there was no evident relationship between these parameters. Most of the parameters are set by the utilities and is often not disclosed openly. An interaction study between the parameters and how their interaction affects the VOS components would be interesting for future studies where utility data are available.

A similar process has been used for the sensitivity analysis of the main VOS. The main VOS's variability has been studied according to the nine VOS components. For each component for which the sensitivity of the VOS is analyzed, average values of the other components are maintained while the studied component's value is varied from its lowest value to its highest value.

4. Results and discussion

The simulation results are plotted first for each VOS components. For each component, sensitivities on the different input variables have been investigated. Then the sensitivity of the overall VOS to each of the VOS components has been analyzed.

4.1. Avoided O&M fixed cost (V_1)

Fig. 1 shows the results for the avoided O&M fixed cost (V_1). The sensitivity has been plotted for five parameters: the utility O&M fixed cost, the utility O&M cost escalation, the PV degradation rate, the utility discount rate, and the utility degradation rate. According to the results, the avoided O&M cost is highly sensitive to the utility O&M fixed cost and O&M cost escalation. When the utility O&M fixed cost increases, the avoided O&M cost increases accordingly and an increase in the O&M escalation rate obviously increases the avoided O&M cost because it increases the utility fixed O&M cost over the analysis period. V_1 is also sensitive to the utility discount rate and decreases when the discount rate increases. This means that using a discount rate close to the social discount rate while conducting a VOS study will increase the avoided O&M cost while using a higher discount rate will lower the cost. This is in accordance with the recommendation of [57] that is the use of a discount rate lower than that of the utility in a distributed solar generation economic calculation. Also, the avoided O&M fixed cost is not very sensitive to the utility degradation rate or the PV degradation rate. Nevertheless, its value is slightly reduced when the PV degradation rate increases.

4.2. Avoided O&M variable cost (V_2)

The parameters for which the avoided O&M variable cost's (V_2) sensitivity has been studied are: the utility O&M variable cost, the utility O&M cost escalation, the PV degradation rate, and the utility discount rate. The sensitivity of the avoided O&M to its parameters are plotted in Fig. 2. Fig. 2 shows a similar variation trend of V_2 as compared to the case of the avoided fixed O&M cost. It is highly sensitive to the utility variable O&M cost, and the O&M cost escalation. The avoided variable O&M cost increases when the variable O&M, or the O&M cost escalation rate is increased but decreases with the increase of the discount rate, and the PV degradation rate.

4.3. Avoided fuel cost (V_3)

In the case of the avoided fuel cost (V_3), the variable considered for the sensitivity analysis are the heat rate degradation rate, the natural gas price fluctuation rate and the PV degradation rate. While the avoided fuel cost has shown to be not very dependent on the heat rate degradation rate or the PV degradation rate, this value changes very quickly with a change in the natural gas price as in Fig. 3. This is an important factor that should be carefully considered while conducting a VOS study because the price of natural gas is not fixed and varies according to

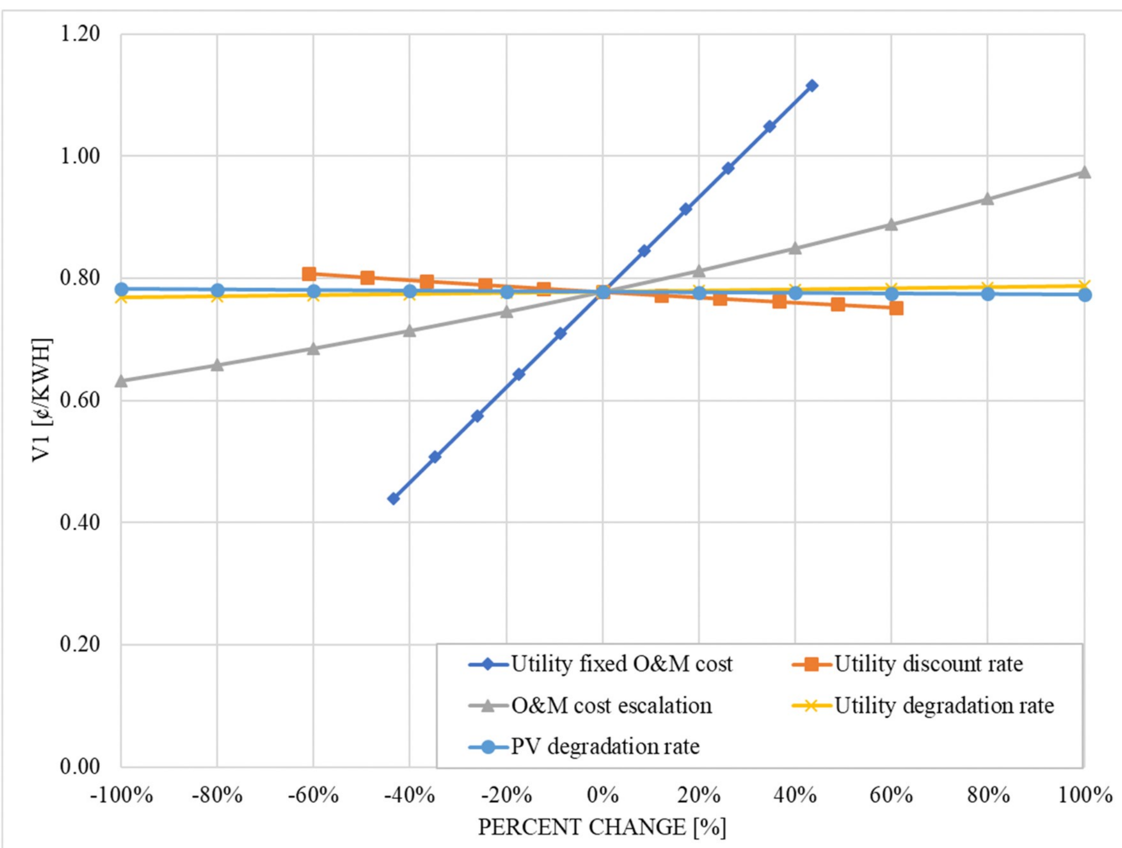

Fig. 1. Sensitivity of avoided O&M fixed cost (V_1) in terms of LCOE (¢/kWh) to its parameters in percent change.

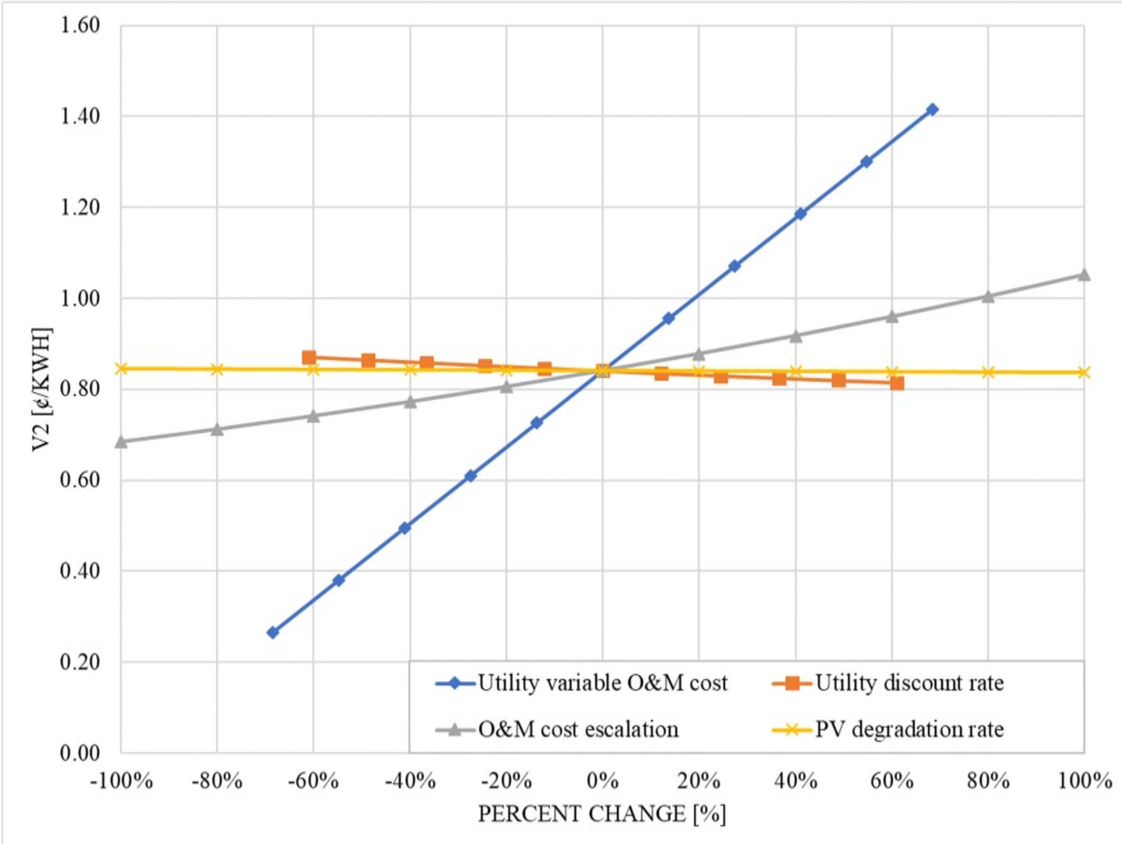

Fig. 2. Sensitivity of avoided O&M variable cost (V_2) in terms of LCOE (¢/kWh) to its parameters in percent change.

several parameters that are not controlled by the utility such as, the economy, the weather, market supply and demand [109,110]. The equivalent heat rate degradation rate expresses the degradation of the utility plant's efficiency over the analysis period and when the efficiency decreases, there is a slight decrease in the avoided fuel cost. Another value for which the avoided fuel's sensitivity could have been studied is the equivalent heat rate for solar, which was not analyzed in detail here because of the lack of utility data. This is left for future work.

4.4. *Avoided generation capacity cost (V_4)*

The sensitivity of the avoided generation capacity cost (V_4) has been plotted in Fig. 4 for the discount rate, the utility degradation, and the PV degradation rate. The V_4 VOS component does not have a high variability to the PV degradation rate even though it shows a decreasing trend with the increase of PV degradation. But it reacts sharply to the utility degradation rate. This is because the generation capacity of the utility is highly impacted by the utility degradation. Also, as previously observed, when the discount rate grows far from the social discount rate, the avoided generation capacity cost decreases.

4.5. *Avoided reserve capacity cost (V_5)*

The avoided reserve capacity cost (V_5) expresses the reserve component of the generation capacity; therefore, it can have a value of zero when there is no reserve capacity planned by the utility as shown in Fig. 5. V_5 is highly sensitive to the reserve margin and the result shows that the more generation capacity is reserved, the more the avoided generation capacity cost increases. On the other hand, the avoided reserve capacity cost is not very sensitive to the discount rate compared to its sensitivity to the other parameters. V_5's value goes up when the utility degradation rate increases and goes down when the PV degradation rate increases.

4.6. *Avoided transmission capacity cost (V_6)*

Three parameters have been analyzed in the sensitivity study of V_6: the discount rate, the transmission capacity cost, and the PV degradation rate. The parameter it is the most sensitive to is the transmission capacity cost. Obviously, when the transmission is low cost in a location, the avoided cost associated will be low. The results shown in Fig. 6 make it clear that the avoided transmission capacity cost does not change with the PV degradation rate or the discount rate. This is because the utility transmission capacity has been assumed to be constant over the analysis period, and the transmission capacity degradation rate has not been considered because utility data on this parameter was not available.

4.7. *Avoided distribution capacity cost (V_7)*

The avoided distribution capacity cost (V_7) is one of the most complicated VOS components to evaluate. As shown in Fig. 7, its sensitivity has been studied for six variables: the load growth rate, the distribution capacity, the distribution capacity cost, the utility discount rate, the distribution cost escalation, and the PV degradation rate. But it depends on more than six parameters. The growth rate, for example is calculated from utility data, mainly, the load for the past ten years of operation [45,111]. Here, the sensitivity has been analyzed on the growth rate directly to be as widely applicable as possible. Another parameter is the number of deferred years that is also a utility owned data.

The avoided distribution capacity cost naturally increases with the distribution capital cost. Fig. 7 shows that the avoided distribution capacity cost does not fluctuate with the distribution capacity at all, but it is highly sensitive to the discount rate, the distribution cost, and the

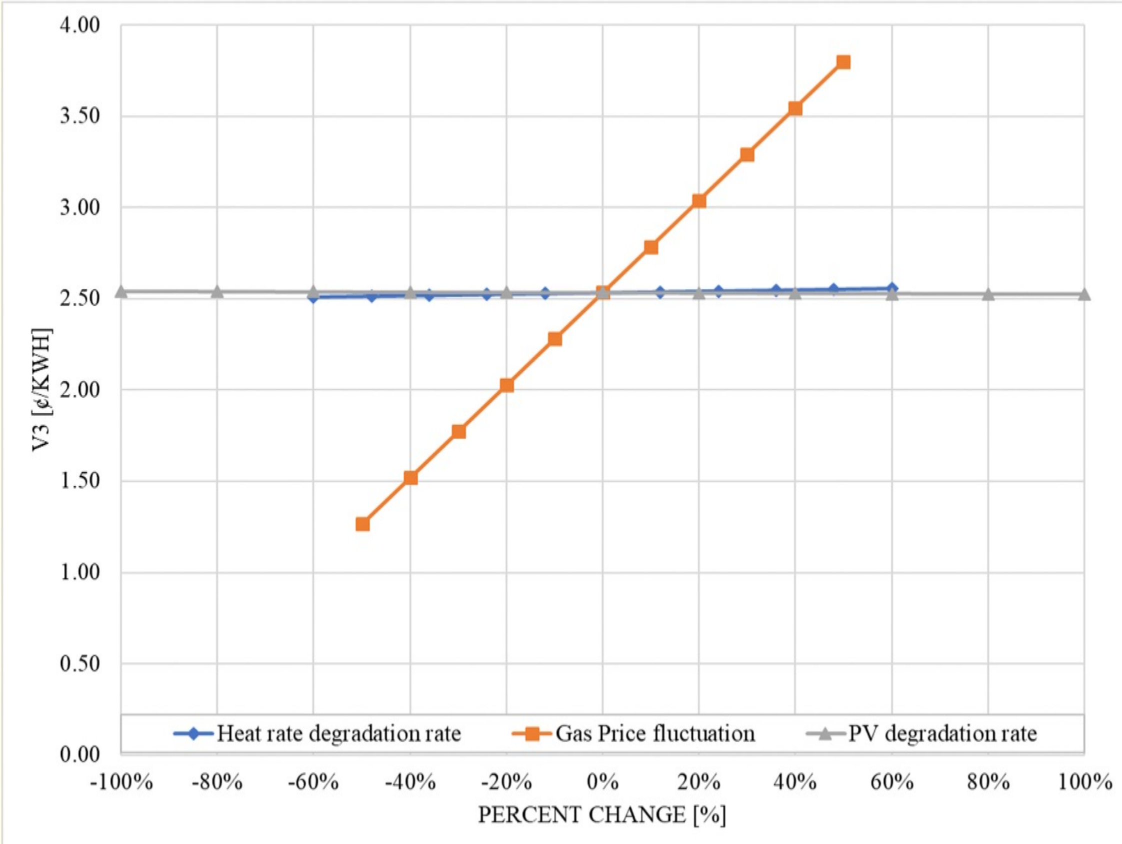

Fig. 3. Sensitivity of avoided fuel cost (V_3) in terms of LCOE (¢/kWh) to its parameters in percent change.

distribution cost escalation rate. It can even shift to a negative value when the discount rate is too low. This shows that choosing the discount during a VOS study must be a trade-off between the social discount rate and the utility discount rate. It is interesting to note that the avoided distribution capacity cost goes down when the distribution cost escalation in increasing. A possible explanation for this observation is that when a utility has enough distribution capacity, it will purchase less power from solar PV systems owners, therefore the price goes down. The same reasoning can be used to explain the decreases of the cost when the load growth goes up. Finally, V_7 shows a slight decrease with the increase of the PV degradation rate.

4.8. *Avoided environmental cost (V_8)*

The second most complicated component of the VOS calculation is the avoided environmental cost (V_8). The sensitivity has been analyzed for the three environmental discount rate scenarios provided by the EPA [81]. For each scenario, a sensitivity analysis has been conducted on the environmental cost increase rate. V_8 will increase when the chosen environmental discount rate is low but overall, each of the three EPA scenarios show an increase when the environmental cost increase rate goes up as seen in Fig. 8. This is useful to see how the avoided environmental costs might change in the future. Environmental externalities are volatile and changing quickly [66]. If it is assumed that in the future, the environmental impact of conventional energy production technologies will increase, then the costs of the environmental externalities will increase as well [104]. On the other hand, an increase in distributed renewable energy generation could lead to a decrease or stabilization of the avoided environmental cost.

4.9. *Avoided health liability cost (V_9)*

The avoided health liability cost, V_9, depends on three values, the health cost increase rate, the environmental discount rate, and the PV degradation (see Fig. 9). This cost does not fluctuate with the PV degradation rate but is very sensitive to the other two parameters. The environmental discount rate used here is the same as the environmental discount rate used in the evaluation of the avoided environmental cost's sensitivity study. As a result, the avoided health liability cost decreases when the environmental discount rate goes up as is the case for the avoided environmental cost.

4.10. *VOS*

After the sensitivity analysis of each VOS component, the main VOS value has been studied to find out how the impact of different components compare to one another and which components have more variability. Fig. 10 shows that the VOS is, in decreasing order, sensitive to the avoided environmental cost (V_8), avoided health liability cost (V_9), avoided transmission capacity cost (V_6), avoided fuel cost (V_3), avoided distribution capacity cost (V_7), avoided O&M variable cost (V_2), avoided reserve capacity cost (V_5), avoided O&M fixed cost (V_1), and avoided generation capacity cost (V_4)

The contribution of each VOS component to the overall VOS depends on the case. The lowest VOS value calculated with the assumptions used in this study in term of LCOE is 9.37¢/kWh while the highest value calculated is 50.65¢/kWh. This variation observed in the VOS value comes from the fact that the parameters values considered from this study are chosen to have the lowest and the highest value of a VOS. The values of calculated VOS using utility data are highly likely to be located within this interval. It is also clear based on the values shown in Fig. 10, that the VOS exceeds the net metering rates (when they are even

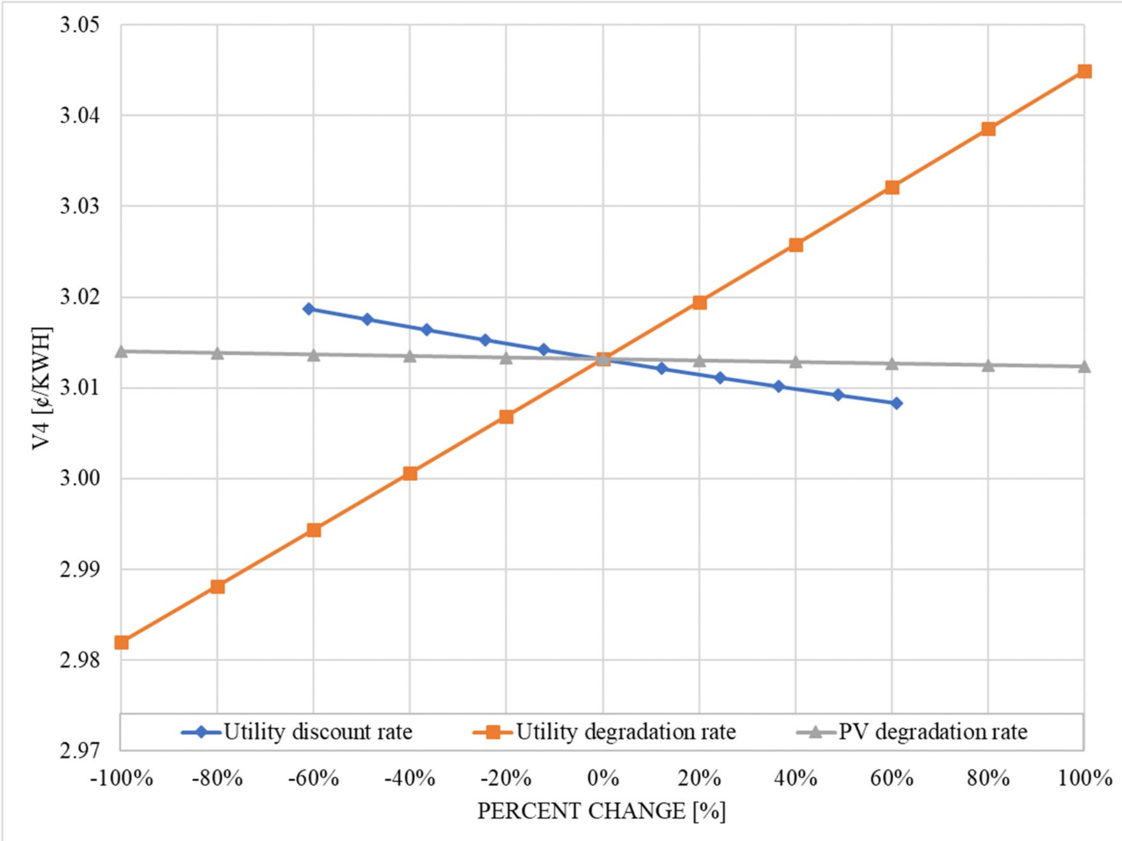

Fig. 4. Sensitivity of avoided generation capacity cost (V_4) in terms of LCOE (¢/kWh) to its parameters in percent change.

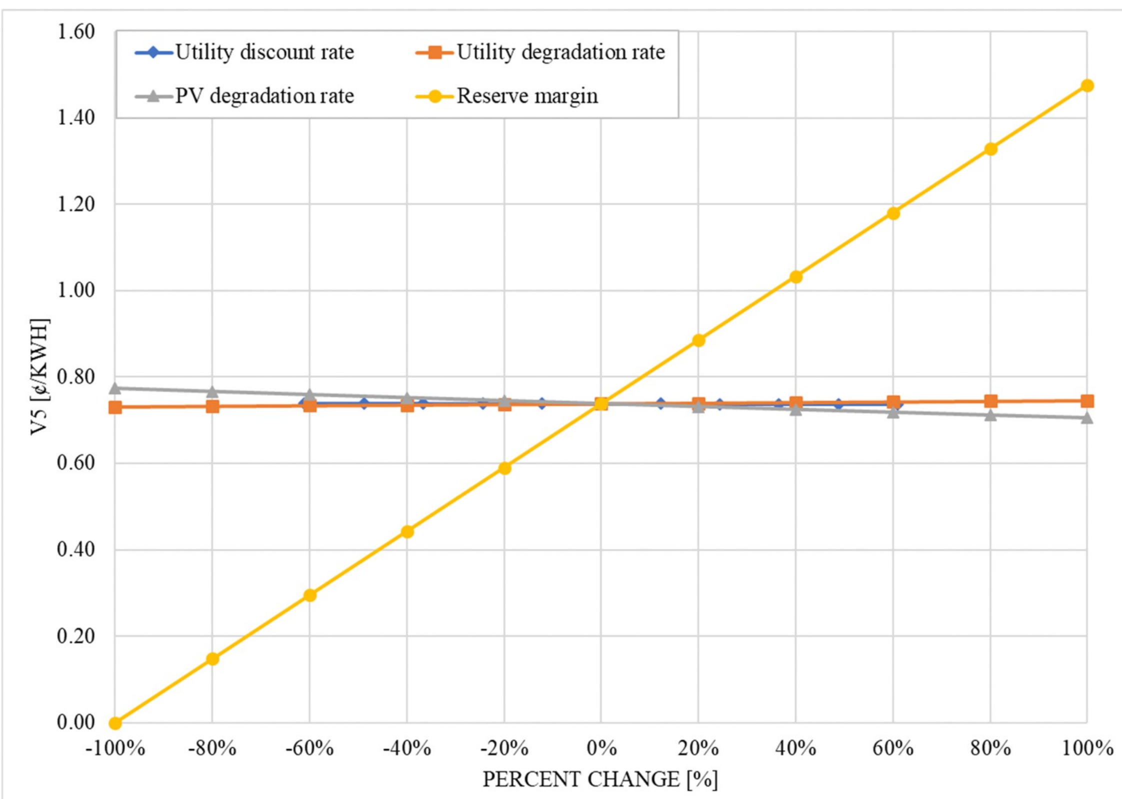

Fig. 5. Sensitivity of avoided reserve capacity cost (V_5) in terms of LCOE (¢/kWh) to its parameters in percent change.

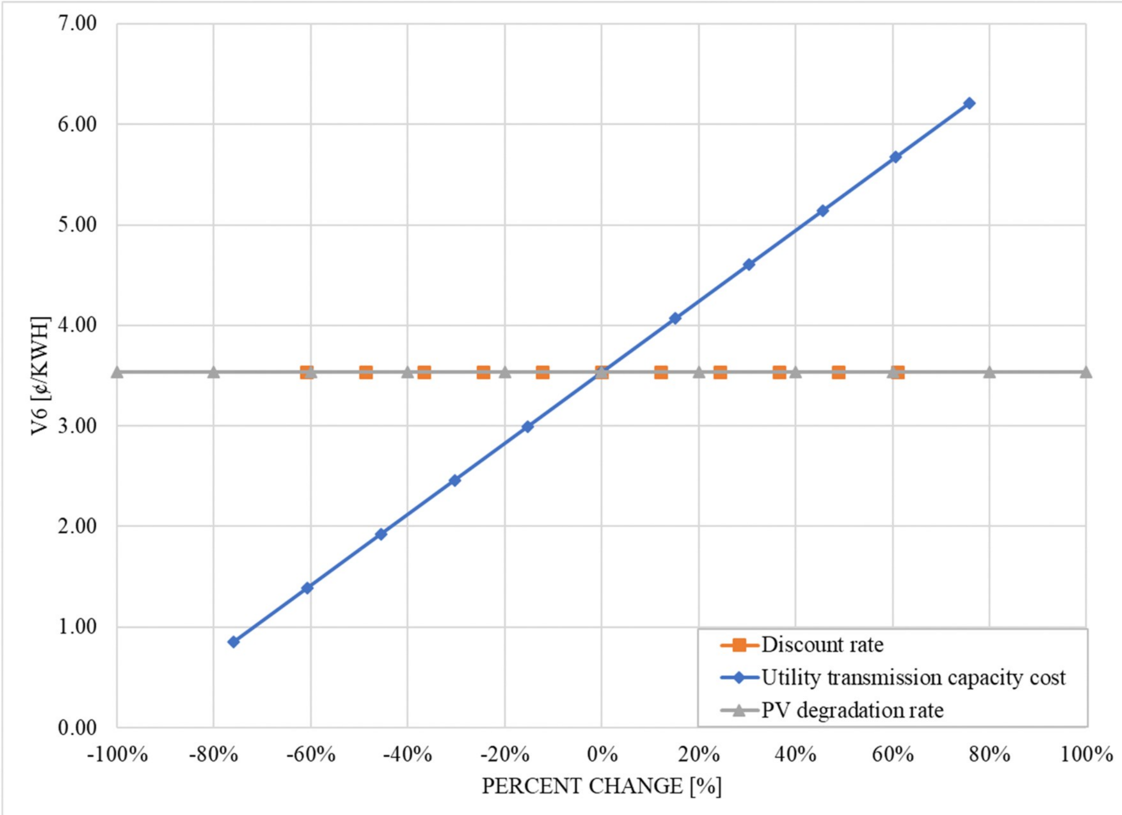

Fig. 6. Sensitivity of avoided transmission capacity cost (V_6) in terms of LCOE (¢/kWh) to its parameters in percent change.

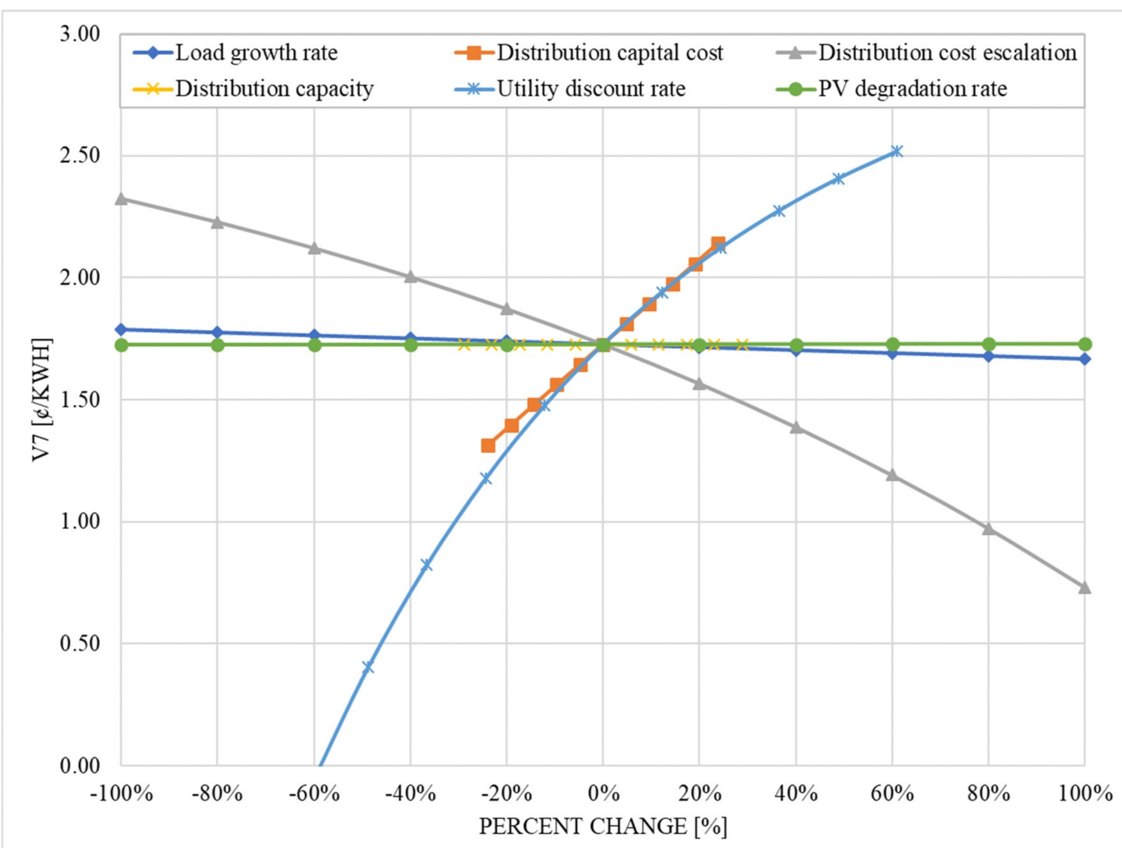

Fig. 7. Sensitivity of avoided distribution capacity cost (V_7) in terms of LCOE (¢/kWh) to its parameters in percent change.

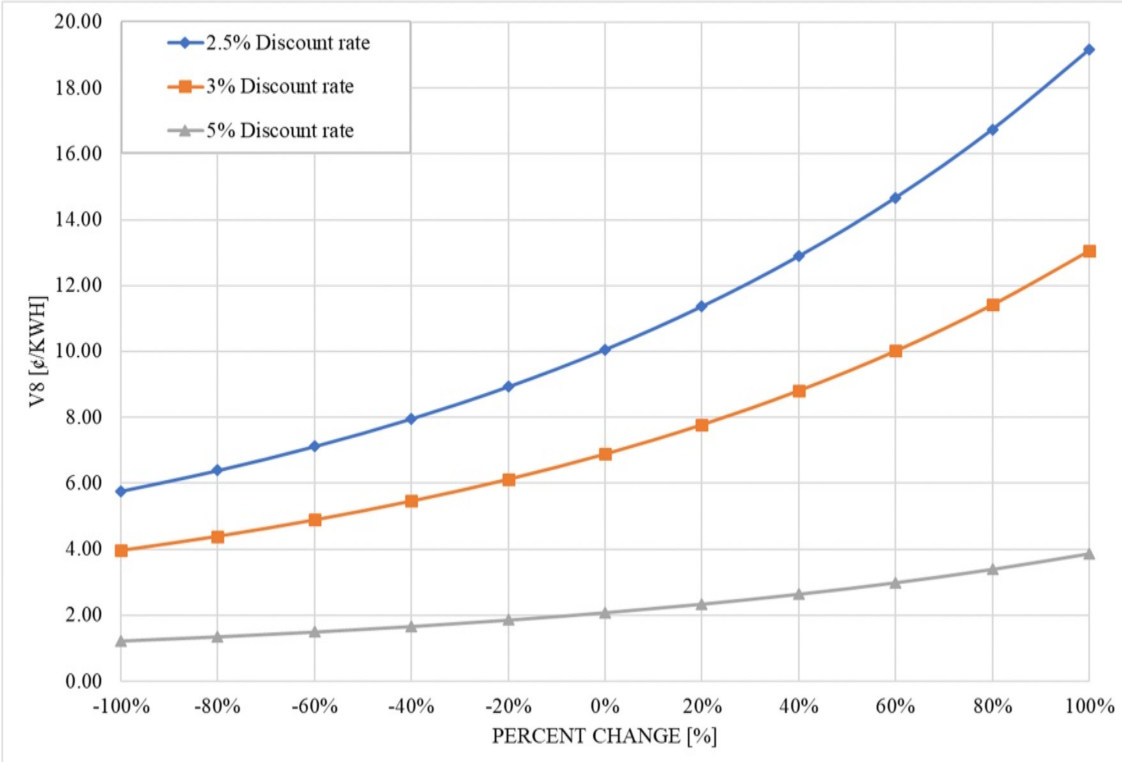

Fig. 8. Sensitivity of avoided environmental cost (V_8) in terms of LCOE (¢/kWh) to its parameters in percent change.

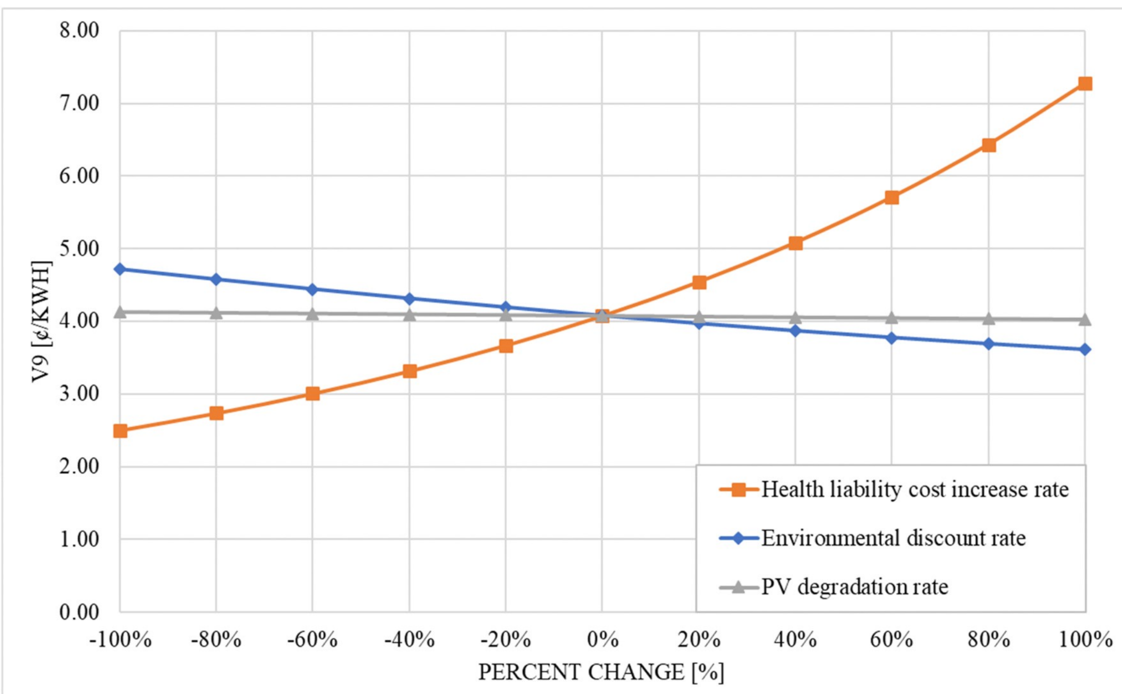

Fig. 9. Sensitivity of avoided health liability cost (V_9) in terms of LCOE (¢/kWh) to its parameters in percent change.

available as shown in Table 2) in the U.S. Thus, it can be concluded that even when grid-tied solar owners are provided with a full net metered rate for electricity fed back onto the grid they are effectively subsidizing the electric utility/other customers.

For the low VOS value case shown in Fig. 11, the avoided distribution cost (V_7), and the avoided reserve capacity cost (V_5) has no contribution in the VOS value. The avoided generation capacity cost (V_4) and the avoided health liability cost (V_9) represent most of the VOS value followed by the avoided environmental cost (V_8) and avoided fuel cost (V_3).

The contribution of the avoided environmental (V_8) cost increases with the VOS value as it becomes the largest contributor to the overall

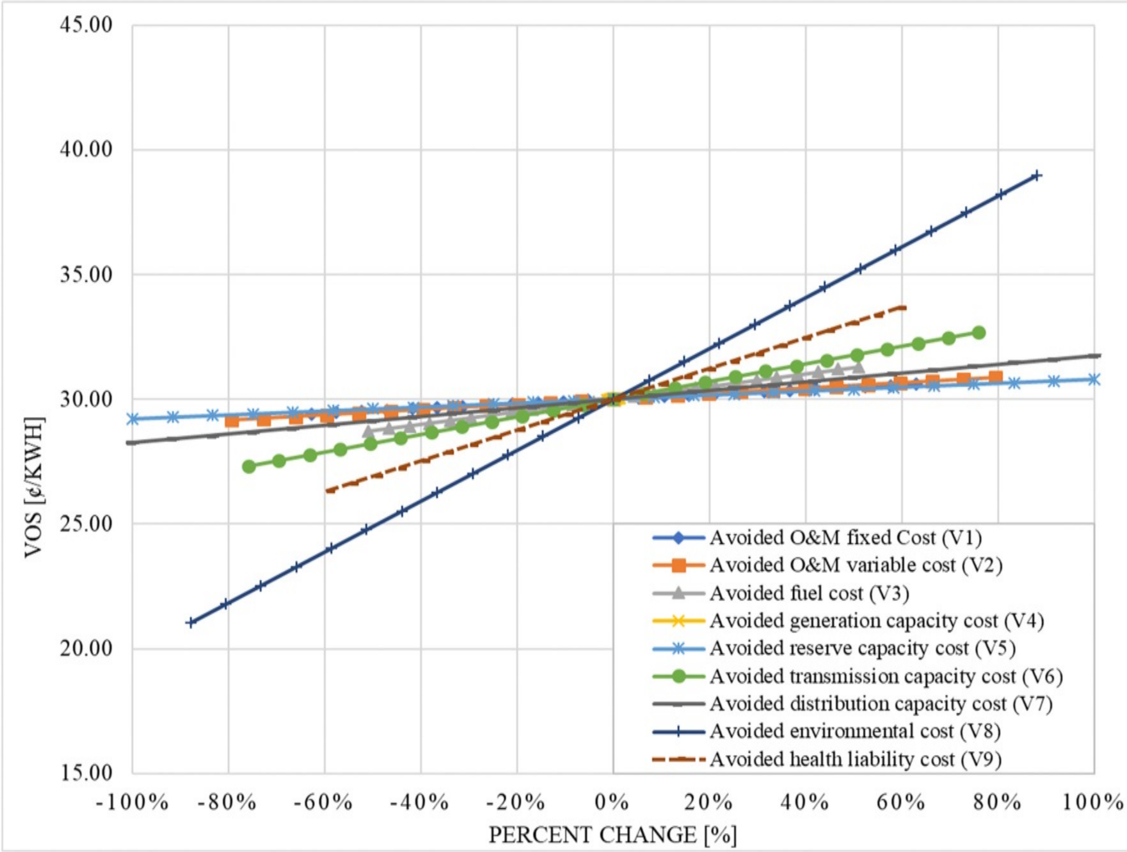

Fig. 10. Sensitivity of VOS LCOE (¢/kWh) to all the components in this study, in percent change.

Table 2
Comparison of VOS rates and net metering rates for some U.S. States.

State	VOS	Net Metering
Minnesota	13.5¢/kWh	
Austin (Texas)	10.7¢/kWh	Approximately 4–5¢/kWh (1.2–1.6$/kWh) [113]
Maine	33.7¢/kWh	12.16–14.66¢/kWh [114]
New Jersey	25.6–28¢/kWh	
Pennsylvania	28.2–31.8¢/kWh	Minimum value of (4¢/kWh) [115]
Washington D. C.	19.4¢/kWh	

value followed by the health liability (V_9) cost as shown in Fig. 12 representing a middle VOS value. The avoided generation capacity cost's (V_4) is reduced as well as the contribution of the avoided fuel cost (V_3).

Fig. 13 represents the contribution of each of the VOS components to the overall value in the case of the highest obtained value in the scope of this study. The avoided environmental cost (V_8), avoided health liability cost (V_9), and avoided transmission capacity cost (V_6) represent 69% of the total cost.

The evolution of the cost percentage contribution of each VOS throughout Figs. 11, Figure 12, and Fig. 13 shows the level of uncertainty of the VOS in respect to the corresponding component.

The lowest and highest LCOE VOS values obtained from the assumptions made in this study are respectively 9.37¢/kWh and 50.65¢/kWh. The existing VOS studies results fall into this interval. The sample calculation made by Ref. [45] for Minnesota is 13.5¢/kWh while [46] calculated a VOS of 10.7¢/kWh for Austin Energy. These values are in the lower spectrum of the result of this study because of the considerations made. They incorporate less VOS components than the present study, and this study focuses on sensitivity, therefore higher values of parameters have been considered. Other results summarized by Ref. [47] have found the VOS to be 33.7¢/kWh in Maine, between 25.6 and 31.8¢/kWh in New Jersey and Pennsylvania [48], and 19.4¢/kWh in Washington DC. In general, the VOS is much higher than the net metering costs as even the highest costs observed at the residential level pay [50,62,112]. The residential net metering rates are also the highest as compared to commercial and industrial rates so the latter two are even more unjustly compensated for installing solar. Overall, this indicates that utilities are under-compensating customers with grid-connected PV systems if they are only paying net metering rates, as displayed in Table 2. Table 2 shows a comparison between VOS rates and net metering rates in the U.S. states mentioned above, wherever data is available. As only a tiny fraction of utilities (3%) are paying full net metering rates anyway [43], there is a need for regulators to ensure that solar customers are being adequately compensated for the value of solar electricity they are sharing with the grid [42]. Substantial future work is needed to ensure that solar PV owners are not subsidizing non-solar electricity customers.

5. Future work

This study has covered a vast number of existing VOS components, but some components were not included in this study due to the lack of a reliable evaluation methodology. These components include the economic development cost, the avoided fuel hedge cost, and the avoided voltage regulation cost. These represent opportunities for future work once the evaluation methodologies have been developed. Also, there are some parameters sensitivities that would provide insights with multiple utility data sets. These parameters include the analysis period, the hourly solar heat rate and solar PV fleet, and the 10-years load profile. Future studies can focus on incorporating the sensitivities of these

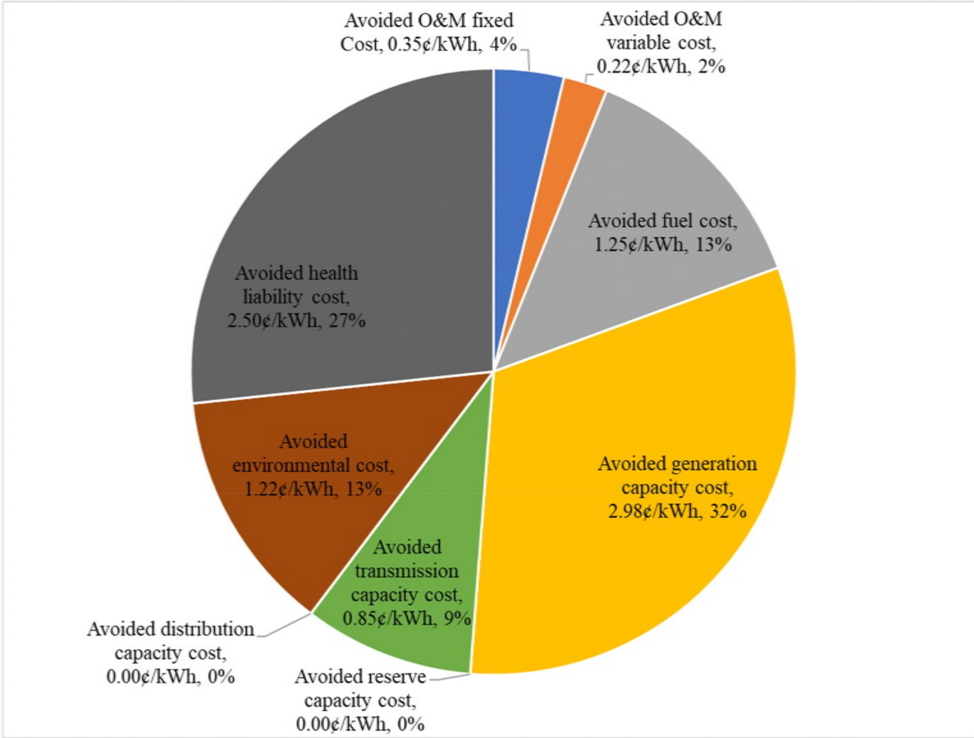

Fig. 11. Contribution of each VOS component to the overall VOS LCOE – Low Cost Scenario.

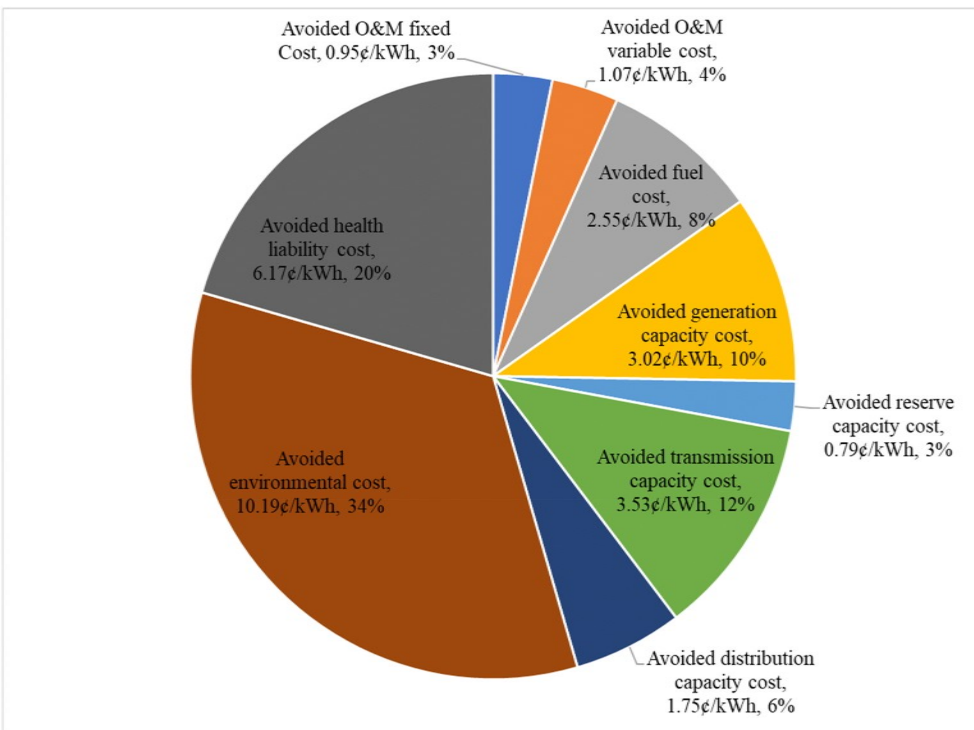

Fig. 12. Contribution of each VOS component to the overall VOS LCOE – Middle Cost Scenario.

parameters into the model or can use the foundation of this model to build on new VOS studies according to a specific location and available data from utilities. Another limitation to this study is that it does not include the effect of the load match factor, and loss saving factor.

As the results show the environmental and health costs can dwarf the technical costs and thereby determine the VOS. There are also second order effects that can be used to obtain a more accurate VOS values. For example, the negative impact of pollution from conventional fossil fuel electricity generation on crop yields [106] as well as PV production could also be considered in future work to give a more accurate V_8. In addition, as greater percentages of PV are applied to the grid the avoided costs will change and there is a need for a dynamic VOS akin to dynamic

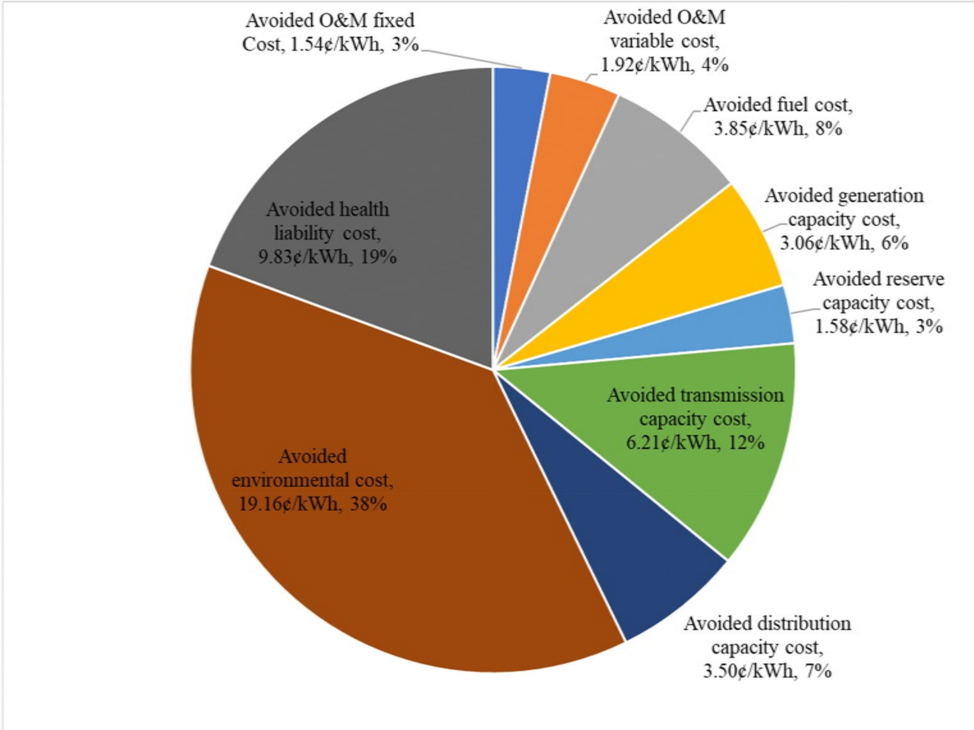

Fig. 13. Contribution of each VOS component to the overall VOS LCOE – High Cost Scenario.

carbon life-cycle analyses needed for real energy economics [116]. This complexity will be further enhanced by the introduction of PV and storage systems [117] as it will depend on size [118] and power flow management and scheduling [119,120].

Perhaps the most urgent need for future work is accurate estimations of the value of avoided GHG liability costs because the magnitude of the potential liability [107,108] could overwhelm other subcomponents of the VOS. This is because as the realities of climate change have become more established, a method gaining traction to account for the negative externalities is climate litigation [107,108,121–131]. For utility VOS analysis this is particularly complex as it is difficult to know where to draw the box around environmental costs. As some studies have concluded there is liability for past emissions as well as for harm done in other nations [122]. Liability for disastrous events is also challenging to predict [126]. Combining both other nations and disaster creates liability potential that could become enormous with prioritization given to victims that are losing their land, culture, and lives due to climate change [127]. Tort-based lawsuits are already possible from a legal point of view [126], but there are other legal methods that could be used to reduce climate change such as public nuisance laws [128]. Some authors have argued a 'polluters pay principle' for carbon emissions [129]. Other studies have concluded that emitters such as conventional fossil fuel power plant operators should be forced to buy long term insurance in order to cover their share of climate change costs for minimizing risks in case of insolvencies [130]. Determining what such insurance premiums should be is another area of substantial future work. Determining what the greenhouse gas liability costs are for conventional electricity generators (as well as potential avoided insurance costs) that can be avoided with PV is extremely challenging. These estimates will become easier with time as climate change impact studies become more granular thereby assigning specific costs to specific amounts of emissions. In addition, realizing these climate liability costs in courtrooms will become more likely. As Krane points out it is clear that as the negative impacts of climate change grow more pronounced, the fossil-fuel based electricity industry faces a future that will be less accepting of current practices and that will increase economic (and maybe even industry existential) risks [131]. Avoiding these risks has real value, which should be included in the VOS in the future.

6. Conclusions

This study demonstrated a detailed method for valuing the incorporation of solar PV-generated electricity into the grid and analyzed the sensitivity of each VOS component to its input parameters, and the overall sensitivity of the VOS to the each of its components. Several components have been found to be sensitive to the utility discount rate, namely the avoided O&M fixed cost; avoided O&M variable cost; avoided generation capacity cost, and the avoided distribution capacity cost. Except for the avoided distribution capacity, the other components' value decreases with the increase of the utility discount rate. The distribution capacity is more sensitive to the discount rate than the other components. It increases with the discount rate and can be negative if the discount rate is very low. This has shown the necessity of carefully choosing the discount rate for VOS studies. Most of the VOS values do not have a high variability to the solar PV degradation rate even though its increase slightly reduces the value of each component, and the overall VOS. The environmental cost and the health liability cost are sensitive to the cost increase rate that can be tied to the emissions impact of the conventional energy sources. These two costs are likely to increase in the future with the worsening of the emission of fossil fuel sources and more information about its effects, which increases potential emissions liability for utilities. Finally, specific case studies could provide additional sensitivities on the few areas of the VOS that were not evaluated in this paper to create better VOS models. Overall the results of this study indicate that grid-tied utility customers are being grossly under-compensated in most of the U.S. as the value of solar eclipses the net metering rate. The implications of this sensitivity analysis demand a reevaluation of the compensation for U.S. PV prosumers as the VOS is much higher than net metering or any lesser compensation schemes. Substantial future work is needed for regulatory reform to ensure that solar owners are not unjustly subsidizing U.S. electric utilities. In addition, future work can obtain an even more accurate (and higher) value of

VOS by evaluating economic development costs, the avoided fuel hedge costs, the avoided voltage regulation costs, secondary health and environmental effects such as increased crop yields from PV-reduced pollution, and accurate estimations of the value of avoided GHG liability costs or avoided GHG emissions liability insurance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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This is to certify that the electronic version of the foregoing is a true and accurate copy of the same document that will be filed in paper medium; that the electronic filing has been transmitted to the Commission on February 24, 2021; that there are currently no parties that the Commission has excused from participation by electronic means in this proceeding; and that in accordance with the March 16, 2020 Commission Order in Case No. 2020-00085 an original and ten copies in paper medium of this filing will not be mailed until after the lifting of the current state of emergency.

Tom FitzGerald