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Abstract

The U.S. housing market has witnessed a rise in the number of low-energy and net-zero energy buildings. Many of them integrate solar photovoltaic (PV) systems to reduce their electricity usage. In predicting the energy performance of a building design and the integrated PV system, builders utilize whole-building simulation programs. These programs either lack consideration of degradation, or are not explicit in the underlying assumptions of the model being used. In our analysis, we use the U.S. Department of Energy's Energy Plus (E+) Whole-building Energy Simulation program, along with alternative degradation model assumptions, to assess the impacts of system degradation on the energy and economic performance of the NIST Net-Zero Residential Test Facility (NZERTF). Alternative degradation rates and models are evaluated to understand the implications of alternative assumptions on system performance and economic viability. The performance sensitivity is compared to the sensitivity of the cost assumption parameters to determine the relative importance of solar PV degradation to the decision-making process.

Assuming linear cumulative degradation and an annual average degradation rate of 0.5 %, a 6.5 % total production loss is realized over a 25 year study period, and leads to an additional $1484 in life-cycle costs from purchasing the 10.2 kW system installed on the NZERTF assuming a 3 % discount rate. An additional sensitivity analysis reveals that the system's economic performance is more responsive to differences in average annual degradation rate assumptions than the assumptions for the assumed degradation model. The variation in economic performance from changes in the degradation rate is comparable to those from the least important cost parameters. The upfront cost of the PV system (installed cost and federal tax credit) is still the most important factor. However, under future economic conditions (e.g. lower realized installed costs) the level of degradation may impact the decision of whether to install a solar PV system.

Keywords

Solar photovoltaics, PV degradation, building simulation, net-zero, energy efficiency; life-cycle costing

Preface

This study was conducted by the Applied Economics Office (AEO) in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). The study is designed to analyze life-cycle energy and economic implications of residential solar photovoltaic performance degradation over the lifetime of the system. The intended audience includes researchers in the residential building sector concerned with solar photovoltaic performance.

Disclaimers

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in metric units first, followed by the corresponding values in U.S. customary units within parentheses.

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List of Acronyms

Acronym	Definition
AEO	Applied Economics Office
APR	Annual Percentage Rate
ASTM	American Society for Testing and Materials
DOE	Department of Energy
E+	EnergyPlus
EL	Engineering Laboratory
EPA	Environmental Protection Agency
EVA	Ethyl vinyl acetate
HVAC	Heating, Ventilation, and Air Conditioning
JPL	National Aeronautics and Space Administration Jet Propulsion Laboratory
LCC	Life-Cycle Cost
LCCA	Life-Cycle Cost Analysis
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NS	Net Savings
NZERTF	Net-Zero Energy Residential Test Facility
O&M	Operation and Maintenance
PID	Potential Induced Degradation
PV	Photovoltaic
SAM	System Advisor Model
TMY3	Typical Meteorological Year 3

1 Introduction

The U.S. housing market has witnessed a rise in the number of newly constructed low-energy and net-zero energy buildings. Along with numerous energy efficiency measures to lower energy use (e.g. additional insulation, high efficiency appliances), homeowners have begun integrating solar energy generation systems to help offset their demands for grid-based electricity. From 2013 to 2014, the number of residential solar photovoltaic (PV) system installations grew 51.0 %. The rising number of residential installations is primarily the result rising electricity prices, declining solar PV system costs, and the existence of financial incentive programs offered by state and federal governments, and utilities. The appeal of solar PV systems lie in the homeowner's anticipation of the ability to recoup the costs of their system through the energy cost savings earned over the lifetime of the system (Darghouth, Barbose et al. 2013).

In an effort to evaluate the overall energy performance of a building design, builders often look to whole-building simulation programs to predict energy use of the design, as well as energy produced on-site through means of a renewable energy generation. These simulation programs generally account for the responsiveness of household consumption and production to local weather conditions and the positioning of the solar array. A shortcoming associated with these programs, however, is that they operate under a variety of assumptions, which may or may not distort energy performance predictions.

Currently available models for solar PV output account for degradation by default. The National Renewable Energy Laboratory's (NREL) System Advisor Model (SAM) incorporates various causes of system performance loss including mismatch, diode and connection losses, and soiling (National Renewable Energy Laboratory (NREL) 2015). PVWatts, a separately available model through NREL, includes both an option for a single degradation rate value to be entered, or for power loss to be calculated based on the cumulative effect of multiple power loss variables (National Renewable Energy Laboratory (NREL) 2015). Current practices indicate that the solar industry is well aware of the importance of solar PV degradation as its effects are included in warranties that guarantee set performance over the PV systems life (Energy Informative 2013, SolarWorld 2015, SunPower 2015). However, building designers and modelers may not be aware of these programs that can supplement the whole building energy modeling software.

Additionally, the residential solar PV market is still considered to be relatively young, leaving a considerable amount of uncertainty regarding the degradation of systems over long periods of time. Minimal measured data exists for PV degradation in residential field applications over system lifetimes given that 97.0 % of PV systems have been installed only in the past 10 years (Timilsina, Kurdgelashvili et al. 2012, Barbose, Darghouth et al. 2013). Despite the lack of measured performance data, it is growing ever more important that modelers consider some degree of system degradation in order to produce more sound evaluations of the energy and economic performance of select residential solar PV systems.

In our study, we assess the impacts of annual solar PV system degradation on the overall energy and economic performance of a net-zero residential dwelling for a 25-year study period using the U.S. Department of Energy's (DOE) EnergyPlus (E+) v8.3 Whole-building Energy Simulation program. Our simulated net-zero energy building design is based on the Net-Zero Energy Residential Test Facility (NZERTF) constructed by the National Institute of Standards and Technology (NIST) located in Gaithersburg, Maryland. The metric for energy performance will be based on calculated net production levels (difference between annual solar PV production and annual energy consumption). In an effort to better understand the effects of alternative degradation pathways on solar PV system performance, we: (1) evaluate three alternative degradation models using a common baseline degradation rate; (2) observe and compare the impacts of four different rates of degradation using a similar degradation model. The economic performance of the NZERTF under all system degradation pathways will be conducted based on existing data for current and projected energy prices, component replacement costs, and maintenance and repair costs; and (3) perform a sensitivity analysis for the purpose of providing insight on the impacts of alternative parameter assumptions (e.g. energy pricing schedule, installation and operating costs, the lifetime of PV system components) as well as those impacts associated with the inclusion of financial incentives and financing options, on the economic performance of the NZERTF. Additionally, we will identify those parameters which most greatly impact economic performance.

2 Residential Solar PV System Applications

2.1 Costs of Solar Photovoltaic Systems

Recent trends in solar PV system installation costs indicate that national average costs have been steadily declining. Installation costs for residential systems have fallen from a median price of $9.00/W in 2007 to nearly $3.29/W as modeled in 2013. These declines in median prices are expected to continue in the near future – however, are expected to do so at a much slower rate (Goodrich, James et al. 2012). Future innovations in solar module production and reductions in balance-of-systems costs do have the potential to drive costs further down though (Rinaldi 2013, Munsell 2015). Some states have witnessed even steeper drops in median prices. Median prices in Maryland have fallen from $12.60/W in 2005 to $4.70/W in 2013 for residential applications. Declines in median installation prices have been realized by all other states as well, despite large price variations across them. Long-term price projections developed by the National Renewable Energy Laboratory (NREL) shed light on further improvements in the affordability of residential systems. They have predicted that the average costs of residential rooftop mounted systems will decline from $5.71/W in 2010 to $2.29/W by 2020 (Goodrich, James et al. 2012).

The rapidly changing nature of the solar PV markets is due to a variety of factors such as economies of scale in PV module production, improvements in system installation learning curves, and increased competition. Reductions in PV module production costs in the recent decade have been a major driver behind recent trends in installation costs. From 2007 to 2013, module production costs have fallen from $4.00/W to under a $1.00/W for systems 10 kW or less. The reductions in PV module costs, however, are expected to level off in the near future (National Renewable Energy Laboratory (NREL) 2013). Significant reductions in non-module system costs have also contributed to declining system installation costs. Non-module system costs include the costs of system inverters, mounting hardware, labor, permitting, and other additional fees. Between 1998 and 2013, the solar PV market witnessed a 42.0 % decrease in system installation costs as a result of a $3.00/W reduction in non-module costs. The role inverter costs plays in non-module cost reductions have been somewhat minimal over the years. From 1999 to 2006, inverter costs per watt have only fallen by 5.0 % to 10.0 % each year. Visible trends in inverter prices have historically been difficult to predict given the large variation in prices and a lack of uniformity in inverter design and performance (Navigant Consulting Inc. 2006). Rates at which average inverter prices have declined consistently fall short of rates related to PV module cost reductions (National Renewable Energy Laboratory (NREL) 2013). However, according to a more recent NREL report, it is expected that residential inverter prices will fall by as much as two-thirds by year 2022 given technological improvements in system inverters – contributing a $0.20/W reduction in system price (Goodrich, James et al. 2012).

2.2 Solar PV Module Degradation

Limited research has been done regarding the degradation of both commercial- and residential-size solar PV systems – in particular, system modules (Dunlop, Halton et al. 2005, Vázquez López and Rey-Stolle Prado 2008, Makrides, Zinsser et al. 2010, Branker, Pathak et al. 2011, Suleske, Singh et al. 2011, Jordan and Kurtz 2013, Ndiaye, Charki et al. 2013). Although a definitive model of PV module degradation has yet to been established, a review of the existing literature does help shed some light on the likelihood of system efficiency loss and the corresponding implications on overall system performance and returns on investment. Table 2-1 summarizes and compares key findings from the literature, as well as a listing of their corresponding sources.

Table 2-1 Solar PV Module Degradation Literature Findings

Authors	General Outcome(s)	Detailed Finding(s)
(Suleske, Singh et al. 2011, Campbell, Zemen et al. 2012, Jordan and Kurtz 2013)	Climate and PV module design are the biggest factors influencing system degradation rates.	Corrosion and discoloration are considered the predominant modes of degradation and both are heavily influenced by climate. Temperature, humidity, and ultraviolet radiation are environmental factors influencing the predominant failure modes.
(Ndiaye, Charki et al. 2013)	Most research attempts to model solar PV degradation as an aggregate value, ignoring the underlying physical causes of the degradation itself.	Field studies look at the aggregated degradation from all effects to obtain an average rate. Reported rates are based on these aggregated values. There is little work on long-term degradation modeling of individual failure mechanisms. The aggregation approach makes understanding the impact of specific degradation types in a PV systems life span difficult.
(Makrides, Zinsser et al. 2010, Jordan and Kurtz 2013)	Degradation rates can vary significantly based on PV module technology.	Amorphous silicon PV modules degrade as much as 13.8 % in the first year, while crystalline silicon first-year rates are in the range of 1.5 % to 4.7 %. All panels quickly stabilize to lower degradation rates in later years.
(Dunlop, Halton et al. 2005, Vázquez López and Rey-Stolle Prado 2008, Branker, Pathak et al. 2011, Suleske, Singh et al. 2011, Jordan and Kurtz 2013)	Various field studies have found that the annual median and average PV degradation rate lies below a 1%.	In examining roughly 2000 reported degradation rates from a summary of observed trends, they discover that the reported median and average degradation rate for crystalline-silicon modules is 0.5 % and 0.8 % each year.
(Sample 2011)	Long-term degradation rates have been found to be less than 1%.	Rates have been found to be in the 0.2 %/year to 1.0 %/year range. Reported rates are similar to rates found in other literature.
(Messaoudi and Bouazzi 2008, Jordan, Wohlgemuth et al. 2012)	Solar panels are generally assumed to have a 25 year life.	Modules have inherintly differing characteristics which become excerbated over time. The standard deviation of the short-circuit current increases for modules, indicating differing module performance. This leads to extensive mismatch, a loss of total system output due to different outputs of individual modules on the string. Corrosion of interconnections and gridlines were also observed.
(Campbell, Aschenbrenner et al. 2008, Fraas and Partain 2010, Darling, You et al. 2011)	Life-cycle costs including solar PV degradation considerations are commonplace.	In calculating the levelized cost of energy the incorporation of solar PV degradation is done to account for the physical reality of a PV system in operation under environmental exposure.

(Ramabadran and Mathur 2009, Sulaiman, Hussain et al. 2011)	Factors not related to degradation also play a large role in power output loss.	Soiling, the collection of particulate matter on PV cells from outdoor exposure, snow cover, and shading all can cause significant power loss despite not technically being forms of degradation of the PV modules themselves.
(Pingel, Frank et al. 2010, Bauer, Naumann et al. 2012)	Alternative forms of degradation inhibit performance.	Potential induced solar (PID) degradation is becoming a greater concern as larger numbers of solar panels become serially connected. PID is a result of the difference in polarity and voltage between the solar PV cell and ground.
(King, Quintana et al. 2000, Dunn, Gostein et al. 2013)	Efforts to minimize production loss caused by browning.	Ethyl vinyl acetate (EVA) browning used to be a major issue in degradation, causing a loss of light transmittance to the solar cells. Those effects have since been reduced with additives and UV blocking glass.

3 Methodology

3.1 The NIST NZERTF Simulation Model Specifications and Assumptions

The net-zero energy building design simulated in our study is based on the NIST NZERTF located on the NIST main campus in Gaithersburg, Maryland (Figure 3-1). The two-story, four-bedroom home has roughly 251.7 m^2 (2709 ft^2) of conditioned floor area and was constructed to show that residential homes can have the "look and feel" of a typical home in the area while reaching net-zero energy consumption through multiple energy efficiency measures combined with a 10.2 kW solar PV system. Following the initial demonstration phase which lasted from July 2013 to June 2014, the NZERTF exceeded net-zero energy performance generating a surplus of 596 kWh (Kneifel, Payne et al. 2015).

Figure 3-1 NIST Net-Zero Energy Residential Test Facility

To evaluate the annual energy performance of the NZERTF building design, we utilize the EnergyPlus 8.3.0 whole-building energy simulation program (U.S. Department of Energy (DOE) 2015). Operation of these programs requires a number of general assumptions and inputs specified by the user. For example, the user must specify what the local weather conditions will be for the simulation environment. Data on the meteorological inputs used to describe local weather conditions in our study are captured by the most recent typical meteorological year (TMY3) weather file constructed using data collected by the local KGAI weather (Weather Analytics 2014). Use of a TMY3 weather data file is consistent with both common building consumption and PV output prediction simulation models.

The NZERTF simulation was designed according to the post-demonstration phase specifications of the facility. Its building envelope is constructed to be "tighter" than identical homes built under typical construction given framing, insulation, windows and air leakage improvements. All electrical and mechanical systems (lighting, heating, ventilation, and air-conditioning (HVAC), and domestic hot water) in the house are energy-efficient. For further details on the NZERTF simulation design specifications and general assumptions, please refer to (Kneifel, Payne et al. 2015).

3.2 Life-Cycle Costing

Life-cycle cost analysis (LCCA) is an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and disposing of a project are considered to be potentially important to that decision (Fuller and Petersen 1996). This study follows the American Society for Testing and Materials (ASTM) International standard method for life-cycle costing of building-related investments (American Society for Testing and Materials (ASTM) International 2013), which involves calculating a stream of cash flow's present value by discounting its future value into today's dollars based on the year the cash flow occurs and the assumed discount rate. Life-cycle cost (LCC) equals the sum of the present value of all relevant cash flows, both positive and negative.

Costs associated with a solar PV system, shown in Equation (1) below, include the initial costs of installing the system ($Cost_{Installed}$), and the present values of maintenance costs ($Cost_{Maint.}$), energy costs ($Cost_{Energy}$), inverter replacement costs ($Cost_{Replace.}$), and residual value of the panels (RV_{Panels}) and inverter ($RV_{Inverter}$). The residual value is what the system is worth at the end of the study period. The maintenance costs are constant and occur annually while the inverter replacement costs occur on an incremental rate. Energy costs occur each year, but escalate over time because energy prices are expected to increase over time.

$$LCC = Cost_{Installed} + Cost_{Maint.} + Cost_{Energy} + Cost_{Replace.} - RV_{Panels} - RV_{Inverter} \quad (1)$$

The LCC to the homeowner from not installing the solar PV system minus the LCC to the homeowner from installing the solar PV system is the Net Savings (NS) of choosing to install the PV system. If NS is greater than zero, then the solar PV system is a cost-effective investment.

3.3 Solar PV System Degradation

Three simplified forms of the degradation rate model are generally recommended when modeling system efficiency loss. The most commonly used is the linear model (Vázquez López and Rey-Stolle Prado 2008, Charki, Laronde et al. 2013, Carullo, Ferraris et al. 2014). In some applications linear degradation is treated as the change in the mean of power output in a Gaussian distribution (Ndiaye, Charki et al. 2013). The linear average rate model used herein does not consider such probabilistic treatment. Alternatively, a general exponential form can be implemented (Chuang, Ishibashi et al. 1997, Xie and Pecht 2003), as well as a variation of the exponential form recommended by the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL) (Pan, Kuitche et al. 2011, Charki, Laronde et al. 2013, Ndiaye, Charki et al. 2013). Equations (2), (3), and (4) below are the linear, exponential, and JPL functional forms, respectively.

$$D(t) = P_0(1 - at) \tag{2}$$

$$D(t) = P_0 e^{-bt} \tag{3}$$

$$D(t) = P_0 e^{-bt^c} \tag{4}$$

Where $D(t)$ is the degraded performance at time "t"
P_0 is the initial power output at time 0
a, b, and c are model parameters

This study considers all three models to examine the implications of alternative degradation model and degradation rate assumptions on the measured performance of the NZERTF's solar PV system performance over the course of its lifetime. Regardless of the functional form, there are limitations with these models. Ndiaye et al. (2013) identifies issues with the use of basic models in practical applications, and suggests a linear rate may not be is valid. Some have discovered that linear rates might be viable, but are subject to further investigation (TamizhMani and Kuitche 2013). The exponential form requires a large number of assumptions and could produce results that may not agree with actual operation. The JPL model is typically used for specific degradation mechanisms, so is dependent on the tests used to determine the coefficients, and testing conditions may not necessarily reflect a real-world operating environment (Ndiaye, Charki et al. 2013).

The degradation rate is generally treated as a deterministic value in standard analysis. Any realistic model of a physical process is likely to include some degree of uncertainty. Jung and Tyner (2014) considered the likelihood of uncertainty by incorporating a probabilistic treatment of system degradation using a Pert distribution for a recent LCCA of a residential PV system in Indiana. Data trends suggest that the standard deviation of PV module performance increases with time – further exacerbating the level of uncertainty associated with system degradation (Muirhead and Hawkins 1995, Berman and Faiman 1997, Reis, Coleman et al. 2002, Sakamoto and Oshiro 2003, Vázquez López and Rey-Stolle Prado 2008). More often than not degradation models are applied without probabilistic considerations. The analysis herein will utilize a deterministic approach.

Based on the literature we have selected an average annual degradation rate of 0.5 % as our base rate. A linear application of the rate will serve as the baseline degradation to mirror practical applications (State of Vermont 2015). Utilizing the JPL model requires two data points to determine its coefficients, so another data point in addition to the base rate must be specified. Vazquez and Rey-Stoll Prado (2008) report typical degradation rates of 1.0 % to 3.0 % per year in the first year of operation. Most of the reported degradation values are in the lower portion of this range – therefore a first year degradation rate of 1.0 % is selected.

Warranty data can be used to determine the limits of degradation manufacturers expect within a slight tolerance; typically between 3.0 % to 5.0 % for manufacturing and measurement (Vázquez López and Rey-Stolle Prado 2008). We refer to the SunPower warranty data to calculate degradation rates and match to the solar panels on the NZERTF. SunPower prescribes a maximum 1.0 % per year power loss over the first five years after installation, and a maximum loss of 0.4 % per year for the remaining 20 years of the warranty (SunPower 2015). Coverage of power losses over expected natural degradation is based on the supplier's analysis of the appropriate ranges to include for manufacturing or installation errors. Warranty data is useful in providing a rough estimate of the minimum expected performance for conducting analyses.

3.4 Data and Assumptions for Initial Analysis

Several initial assumptions are required to conduct our LCCA comparing the total costs of energy use by the NZERTF without solar PV to those realized when adopting a small residential system that linearly degrades over time. Table 3-1 summarizes all assumptions for the initial analysis. The assumed average annual degradation rate is 0.5 %. Please see (Kneifel, Payne et al. 2015) for further information regarding the specifications of the NZERTF and the on-site solar PV system.

Table 3-1 Parameter Assumptions for Baseline Life-Cycle Cost Analysis

Parameter Assumptions for Baseline Life-Cycle Cost Analysis for the Solar PV System		
Parameter	**Value**	**Source**
Length of Study Period (years)	25	(Author's Assumption)
Household electricity consumption	11 684	(Kneifel 2014)
(kWh/year)	15.3	(Kneifel 2014)
Real electricity price (cents/kWh)[1]	10.2	Based on E+ simulation
Installed PV capacity (kW)	15 135	(Kneifel 2014)
Annual PV production (kWh/year)	8.7	(Kneifel 2014)
PV production price (cents/kWh)[2]	25	(Author's Assumption)
PV panel service life (years)		
Real O&M Costs ($/kW-year)[*]	20	(National Renewable Energy Laboratory (NREL) 2013)
System installation cost ($/W)	3.71	(Feldman, Barbose et al. 2014)
Inverter replacement (years)	10	(Heacox 2010)
Inverter replacement cost ($/W)[3]	0.57	(Goodrich, James et al. 2012, Liu, Eric et al. 2014)
Grid connection fee ($/kW)	0	(Author's assumption)
Federal tax credit	0%	(Author's assumption)
Residual value	None	(Author's assumption)
Real discount rate	3%	(Lavappa and Kneifel 2015)
Degradation module	Linear	(Charki, Laronde et al. 2013)
Average degradation rate	0.5	(Jordan and Kurtz 2013)
Loan financing percentage	-	(Author's assumption)
Loan financing period (years)	-	(Author's assumption)
Loan interest rate	-	(Author's assumption)

The parameter values in Table 3-1 help establish our baseline case. Values were chosen to be within typical ranges of reported values so that the model will be representative of some midway condition between various extreme cases. The baseline assumes that annual household electricity consumption is 11 684 kWh and solar PV production is 15 135 kWh for the first year. Other assumptions include cash purchase of the PV system, no financial incentives, no grid connection fee, excess electrical value of $0.087/kWh, service life of 25 years, yearly operation and maintenance (O&M) costs of $20/kW, and inverter replacement rate of 10 years at a cost of $0.57/W. We assume a 3.0 % discount rate based on DOE's real discount rate for federal energy efficiency projects, which is comparable to the return on investment for a low (no) risk investment in U.S. treasury bonds (Lavappa and Kneifel 2015). A residual value of "0" is assumed, treating the end-of-service life for the system as the end-of-usage.

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[1] The real cost of electricity to the household is 15.3¢/kWh in the first year. Annual escalation in electricity prices in the subsequent years is based on the U.S. Department of Energy's energy price escalation projections.

[2] The twelve-month average marginal generation charge for any excess generation (net-metering) for local PEPCO customers (Kneifel 2014).

[3] Includes the labor cost for replacement. Total labor costs were calculated by adding together the levelized cost of labor (15¢/W) taken from Liu, O'Rear et al. (2014), and a labor cost of 42¢/W from Goodrich, James et al. (2012). Value is close to the assumed replacement costs of 60¢/W and 55¢/W reported by Horizon Energy. Systems (2009) and the State of Vermont (2015), respectively.

3.5 Sensitivity Analysis

Results derived using our baseline parameter assumptions provide a limited picture of the economic performance of the solar PV system. Therefore, a sensitivity analysis is conducted to test how robust our baseline findings are to changes in important parameter assumptions. Table 3-2 displays the alternate parameter values, most of which are representative of upper and lower bound estimates found in the existing literature. A number of alternative cases based on the parameter changes will be considered in the additional analysis. Some cases will showcase the implications of alternative degradation rate structures on PV performance and the aligning economic performance. Others will examine how offsetting initial investment costs through either a federal tax credit or a home-equity loan may make the system more cost-effective.

Table 3-2 Parameter Values for Sensitivity Analysis

Changes in Baseline Parameter Assumptions for Sensitivity Analysis		
Parameter(s)	**Value**	**Source**
PV Panel Service Life	40 years	(National Renewable Energy Laboratory (NREL) 2013, SunPower 2013)
System Installation Costs	$4.69/W	(Feldman, Barbose et al. 2014)
	$3.29/W	(Feldman, Barbose et al. 2014)
EPAct Tax Credit	30 %	(Environmental Protection Agency (EPA) 2015)
Grid Connection Fee	$3.00/kW*	(Wesoff 2015)
Loan Financing Percentage/Interest Rate	80 %/4.88 %	(Jung and Tyner 2014)
O&M Costs	$32.80/kW-year	(Liu, Eric et al. 2014)
	$7.42/kW-year	
Inverter Replacement Costs	$0.90/W	(Liu, Eric et al. 2014)
	$0.42/W	(Goodrich, James et al. 2012)
Inverter Replacement (years)	15 years	(Navigant Consulting Inc. 2006)
Residual Value	40-year (Energy)	(Author’s Assumption)
	40-year (Proration)	(Jung and Tyner 2014)
Discount Rate	5.0 %	(Author’s Assumption)
	8.0 %	(Author’s Assumption)
Degradation Model	Baseline Rate – Exponential	(Ndiaye, Charki et al. 2013)
	Baseline Rate – JPL	(Pan, Kuitche et al. 2011)
	Warranty – Piecewise Linear	(SunPower 2015)
	Warranty – Exponential	(Author’s Assumption)
	Warranty – JPL	(Author’s Assumption)
Average Degradation Rate	0.0	(Author’s Assumption)
	0.25	(Author’s Assumption)
	0.80	(Author’s Assumption)
	1.0	(Author’s Assumption)

*** Flat Rate Connection Charge**

All sensitivity analysis variables assume the baseline 25-year service life with the exception of residual value, which assumes a 40-year useful life, 15 years of residual life in addition to the 25-

year service life (National Renewable Energy Laboratory (NREL) 2013, SunPower 2013) and two different approaches to approximate system value at the end of a 25-year study period. This is notably different than the 25-year life prescribed in the literature review, however the solar PV system will still produce electricity beyond 25 years barring a catastrophic failure (Dunlop and Halton 2006). Instead it would be expected that wear-out would eventually cause system failure. Though used for analysis purposes, the 40-year life with 0.5 %/year linear degradation is admittedly an over-simplification. Consideration of the system's residual value (the remaining value of an asset after it has been fully depreciated) will be done in one of two ways, both discounted to NPV: (1) using a valuation of energy savings given a 15-year residual life; and (2) a linear proration of the initial cost (Fuller and Petersen 1996). The primary costs associated with the purchase of a residential PV system are the initial system costs. We evaluate the impacts of two alternate system installation cost estimates on total LCC calculations, at roughly 26.0 % higher and 11.0 % lower.

The Energy Policy Act of 2005 established a tax credit, which was recently extended, that allows taxpayers to claim a 30.0 % federal tax credit for residential solar-electric, solar water heating, and fuel cell systems through 2019 before dropping to 26.0 % percent in 2020, 22.0 % in 2021, and eventually disappearing in 2022. Unlike the baseline case, which did not include this credit in its LCC analysis, the sensitivity analysis looks to reveal the implications of offsetting initial system costs by way of the federal tax credit.

Utilities and regulators have expressed concern over the inability of current electricity rate structures to account for the unique benefits the electricity grid offers to homeowners with solar PV system – one of them being the ability to use the grid as storage for generated electricity (net-metering) without having to pay for the service (Darghouth, Wiser et al. 2015). A monthly $3.00/kW grid connection fee is considered to gain insight on the impacts of net metering costs on overall system affordability.

Providing homeowners with an opportunity to finance solar PV systems allow them to obtain the system while spreading payments out over a fixed number of years. The baseline assumed the homeowner pays for the system upfront in cash. Our sensitivity analysis uses an 80.0 % financing option where the homeowner receives a loan at 4.88 % APR (Annual Percentage Rate) for 80.0 % of the initial system cost, and is responsible for 20.0 % upfront (down payment).

The DOE energy price escalation rate used in the baseline amounts to a 20.0 % increase in energy prices by the final year of service life in this study. The impacts of doubling this rate (details not reported in Table 3-2) will be observed in the sensitivity analysis, as well as the effects of no price escalation. Researchers Jung and Tyner (2014) assume an O&M cost of $0.005/kWh. Our sensitivity scenario examining an O&M cost of $7.42/W-year is based on a conversion of the dollar per kilowatt-hour values based on the output of the 10.2 kW system given the TMY3 weather file output. The converted cost per watt is treated as constant based on installed wattage. Liu et al. (2014) assume that replacing an inverter for a 4 kW system costs

$3600. The levelized $0.90/W replacement cost for an inverter reported in Table 3-2 for our sensitivity analysis is based on these assumptions.

Alternative pathways for system efficiency losses related to the three aforementioned degradation models and degradation rates were not considered in the baseline. Our additional sensitivity analysis will consider the impacts of alternative degradation rates (i.e. 0.0 %, 0.25 %, 0.75 %, and 1.0 %) assuming linear degradation of the system on total life-cycle costs and net savings. Currently, the exponential and JPL formulas for PV degradation are not widely utilized in current literature, which tends to lean more towards the use of the linear formula. We will evaluate the impacts of the three degradation models based on two different assumptions for the annual degradation rate. The first being the 0.5 % rate considered in the baseline, and the other being an average rate calculated using system warranty data. As it is specific to the installed system, using warranty data will not necessarily generalize beyond the specific system being analyzed. The responsiveness of the baseline results to changes in each of the parameters listed in Table 3-2 will be compared across three discount rates: 3.0 %, 5.0 %, and 8.0 %.

4 Results and Discussion

In this section, we evaluate the impacts solar PV degradation has on the energy and economic performance of the NZERTF's solar PV system. Additionally, sensitivity analysis is completed to evaluate the robustness of the results across different solar PV degradation rates and models as well as a variety of cost-related assumptions from the analysis.

4.1 Energy and Economic Performance of the NZERTF Solar PV System with Linear Degradation

The functional form of the cumulative linear degradation model expressed in terms of the percentage of initial power output[4], with an annual average degradation of 0.5 %, is shown in Equation (5) below:

$$D_{\%}(t) = 1 - 0.005t \quad (5)$$

According to the above equation, after *t* number of years, the loss in operating efficiency for the system would be approximately $t \cdot 0.05$ %. An illustration of the cumulative linear degradation over the course of a 25-year study period is shown in Figure 4-1. The 10.2 kW system realizes an efficiency loss of 12.5 % by year 25. Assuming *ceteris paribus*, the system would have to be operating for more than a century before it even realizes a loss of efficiency of 50 % or more.

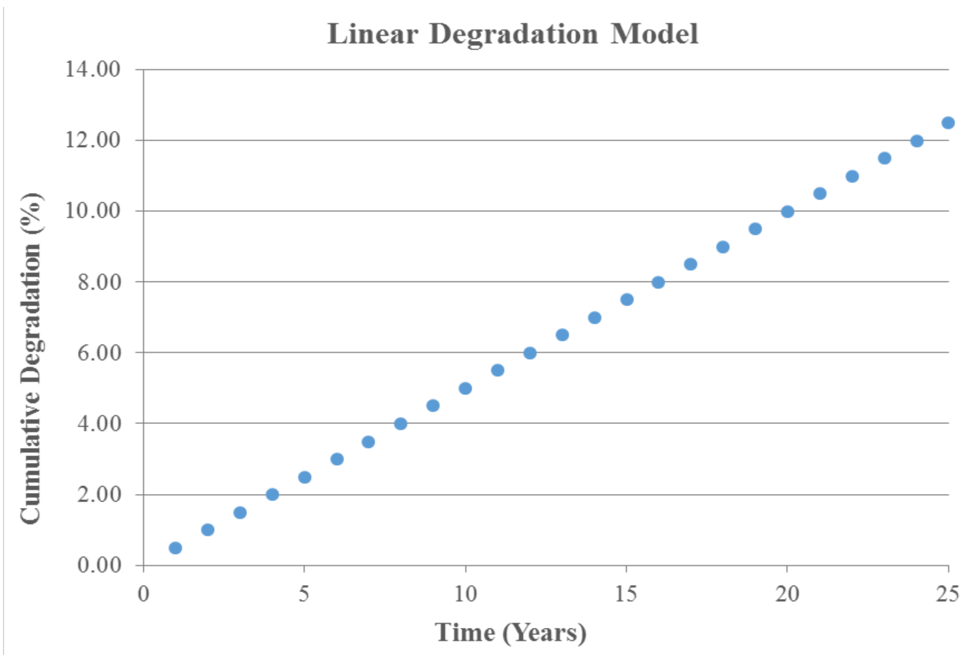

Figure 4-1 Cumulative Linear Degradation Plot

[4] To calculate cumulative percentage the initial power output, P_0, is assumed to be 1.

Figure 4-2 plots the cumulative linear degradation trajectory applied to projected yearly energy production. If the system experiences zero efficiency loss, total electricity production would be 378 365 kWh over 25 years. A yearly degradation of 0.5 % would lead to 353 772 kWh of aggregated electricity generation – a 6.5 % loss. In other words, 12.5 % efficiency loss over the life of the system equates to 1892 kWh of lost annual electricity production in year 25. Use of a simplified linear degradation model reveals that the homeowner still stands to recoup a significant amount of energy savings over 25 years.

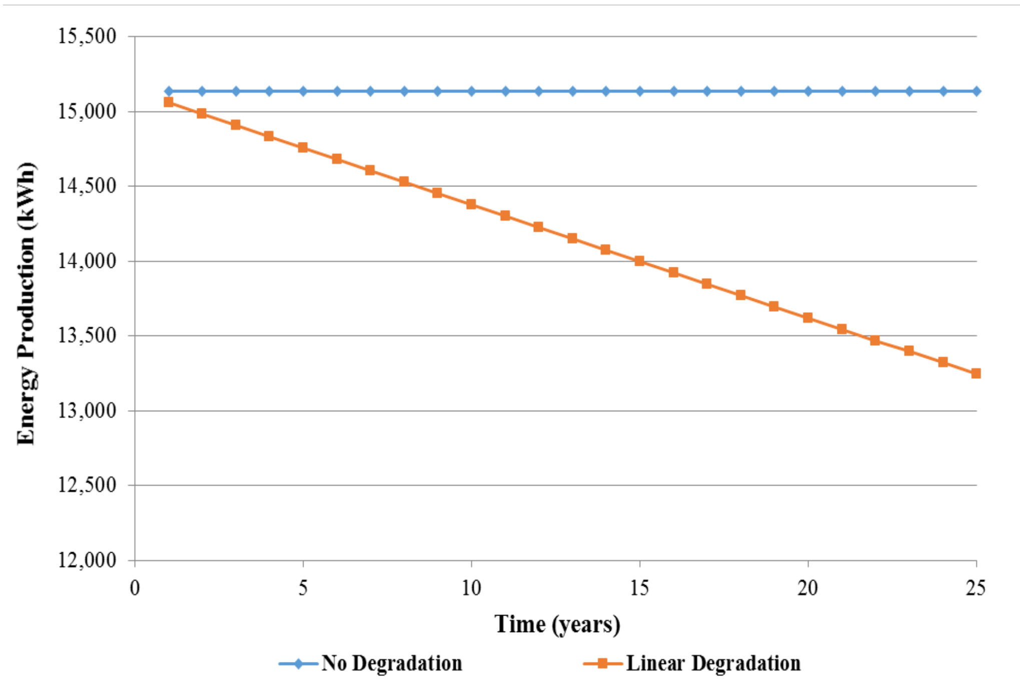

Figure 4-2 Annual Solar Electricity Production Subject to System Degradation

A primary driver behind decisions to purchase residential solar PV systems is the estimated cost implications to the owner. Table 4-1 shows the LCC (sum of energy costs and solar PV-related costs) and NS calculations for three different cases for a homeowner: (1) the NZERTF without a solar PV system installed; (2) the NZERTF with a 10.2 kW system assumed to operate at 100 % efficiency (zero degradation) throughout an assumed 25-year lifetime; and (3) the NZERTF with a 10.2 kW system assuming a linear degradation rate of 0.5 % annually. The analysis is based on the assumptions defined in Table 3-1.

Table 4-1 Life-Cycle Cost Analysis (3% Discount Rate)

Cost Measures		Degradation Rate	
		0.5 %	0.0 %
LCC	No Solar PV	$34 238	$34 238
	Baseline PV System	$44 673	$43 189
Net Savings (NS)		($10 435)	($8951)

Without a solar PV system, present value energy costs over the 25-year study period are projected to be $34 238. Under the assumption of zero degradation, the NZERTF with the solar PV system installed is projected to have present value costs of $43 189, which is a net savings (NS) of -$8951. The inclusion of a 0.5 % linear degradation rate leads to a reduction in electricity production by the solar PV system over time, which leads to greater present value LCCs ($44 673) and a decrease of $1484 in net savings to -$10 435. Under the baseline assumptions, the solar PV system is not cost-effective relative to not installing the solar PV system indifferent to a 0.0 % or 0.5 % degradation rate. However, under different assumptions, the change in net savings could impact a decision-makers' choice.

4.2 Sensitivity Analysis

Given the quantity of parameters necessary to calculate the energy and economic performance of the solar PV system on the NZERTF, it is necessary to consider how sensitive the results are to changes in the assumptions. By completing a sensitivity analysis, it will be possible to determine the importance of the assumed degradation rate relative to the cost-related assumptions.

A summary of net savings in present value LCC relative to the no solar PV system alternative for alternative degradation rates and degradation models across three discount rates (3.0 %, 5.0 %, and 8.0 %) is shown in Table 4-2. Discount rates are used to account for the time value of money, or a decision-makers' expected return from their next best alternative investment of equivalent risk and duration. Higher discount rates imply higher expected return on investments and higher associated risk. Evaluation across three different discount rates sheds light on differences in the economic performance for the investment under different rates of return (and risk levels).

Higher discount rates will lead to the energy cost savings from the solar PV system being worth less in present value terms. The baseline PV system leads to negative net savings under all three discount rates. As expected, an increase in the degradation rate leads to a decrease in the net savings. However, the assumed degradation rate does not impact the homeowner's decision under any discount rate..

Table 4-2 Sensitivity Analysis Results – System Degradation

		3.0%	5.0%	8.0%
Case	**Value**	**NS**	**NS**	**NS**
No PV System	NA	0	0	0
Baseline PV System	0.5 - Linear	($10 436)	($15 389)	($20 495)
Average Degradation Rate	0	($8951)	($14 292)	($19 771)
	0.25	($9694)	($14 841)	($20 133)
	0.8	($11 326)	($16 048)	($20 929)
	1.0	($11 989)	($16 529)	($21 240)
Degradation Model (13% in 25 Years)	Baseline Rate – EXP	($10 818)	($15 705)	($20 738)
	Baseline Rate – JPL	($10 471)	($15 418)	($20 516)
	Warranty – PL	($10 652)	($15 568)	($20 634)
	Warranty – EXP	($10 831)	($15 714)	($20 745)
	Warranty – JPL	($10 940)	($15 805)	($20 815)

The impacts of alternative degradation models on net savings are directly tied to the size of production losses given different efficiency loss models. Plots of the cumulative degradation percentages for each of the degradation models listed in Table 4-2 are illustrated in Figure 4-3. It shows that for both the 0.5 % and the warranty degradation rates, the linear model proves to be the most optimistic within the 25-year study period, which is the same length as the warranty period of the solar PV panels.

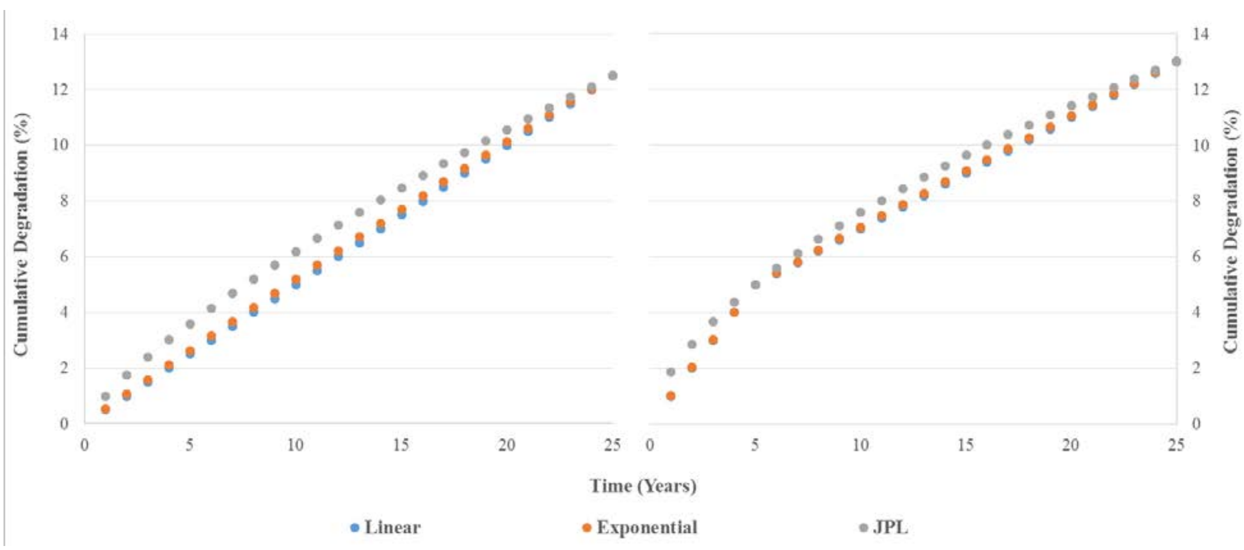

Figure 4-3 Degradation Trajectories at the (a) base rate and (b) warranty rate

A ranking of the degradation models from most to least optimistic in terms of measured efficiency loss is displayed in Table 4-3 below. It also includes model functional forms in terms of percentage of initial power output[5].

Table 4-3 Ranking of Degradation Models from Most to Least Optimistic

Rank	Model	Functional Form
1	Base Rate – Linear	$D_{\%}(t) = 1 - 0.005t$
2	Base rate – Exponential	$D_{\%}(t) = e^{-0.0674t}$
3	Base rate – JPL	$D_{\%}(t) = \exp[-0.0101t^{0.804}]$
4	Warranty – Piecewise linear	$D_{\%}(t) = \begin{cases} 1 - 0.01t, & for\ 1 \le t \le 5 \\ 1 - 0.004t, & for\ 5 < t \le 25 \end{cases}$
5	Warranty – Exponential[6]	$D_{\%}(t) = \begin{cases} e^{-0.0103t}, & for\ 1 \le t \le 5 \\ 0.971e^{-0.00440t}, & for\ 5 < t \le 25 \end{cases}$
6	Warranty – JPL	$D_{\%}(t) = \exp[-0.0189t^{0.621}]$

Based on Figure 4-3, it is clear that the linear and exponential models under both degradation assumptions are nearly identical over the 25-year period. How close the two models are and how their long-term relationship develops is dependent upon where the degradation rate is applied in the exponential model. Vazquez and Rey-Stolle Prado (2008) apply a 0.5 % degradation rate in the first year. This study assumes that the rate is applied in a cumulative fashion at the end of the service life.

Selecting alternative degradation models lead to slightly smaller net savings than the linear degradation model, ranging from -$10 940 to -$10 471 (see Table 4-2). The largest difference in net savings relative to the baseline PV system results from implementing the JPL degradation model ($504), which is equivalent in impact of a 0.17 % change in the degradation rate using a linear degradation model.

It is important to note that the base rate JPL model is sensitive to the first-year degradation rate. A more optimistic (pessimistic) assumption of initial degradation yields a more optimistic (pessimistic) model within the warranty period. Furthermore, if the first-year value is less than the degradation rate in the final year, the JPL model will change concavity and become more optimistic in the warranty period. This sensitivity requires two accurate data points to provide a realistic fit for the model. In the absence of any justifiable secondary data point, the JPL model becomes as, if not more, arbitrary than the linear model.

Table 4-4 summarizes the NS results relative to the no solar PV system alternative across the cost-related parameter values. Net savings values are derived by taking the difference in LCC between the "No PV system" case and each case accounting for a change in the underlying

[5] To calculate cumulative percentage the initial power output, P_0, is assumed to be 1.
[6] Due to the piecewise nature of the warranty, a piecewise exponential distribution is created with the condition that $D(t \to 5^-) = D(t \to 5^+)$; no further continuity constraints are applied.

baseline parameter. The ΔNS measure in Table 4-5 is the incremental change in NS caused by changes in parameter assumptions relative to our baseline case.

The initial cost to the homeowner, which includes the installed cost and associated financial incentives, leads to the greatest impacts on the cost-effectiveness of installing a solar PV system. At $4.69/W, the solar PV system is even less cost-effective. The PV system being installed at a lower cost ($3.29/W) leads to greater, but still negative net savings (-$6152) relative to the baseline (-$10 436) assuming a 3.0 % discount rate. However, the lower installed cost cannot make the solar PV system cost-effective. The federal tax credit (30 % of installed cost) is the only parameter that leads to the solar PV system being cost-effective for a 3 % discount rate, which shows the importance of the tax credit (as well as other financial incentives) in the decision-making process of installing a solar PV system. However, there is no set of assumptions considered in this study that make the solar PV system cost-effective assuming a 5 % or 8 % discount rate. The preferred financing option (cash versus 80/20 loan at 4.88 %) for the solar PV system varies based on the discount rate. A homeowner would prefer to purchase a solar PV system with a loan when the interest rate is lower than the discount rate, which is supported by the fact that the net savings for the baseline PV system is greater than the financed option for a 3.0 % discount rate but not for a 5.0 % discount rate.

Table 4-4 Net Savings Relative to No Solar PV System

		Discount Rate		
		3.0 %	5.0 %	8.0 %
Case	**Value**	**NS**	**NS**	**NS**
Baseline PV System		($10 436)	($15 389)	($20 495)
Installation Costs	$4.69/W	($20 432)	($25 385)	($30 491)
	$3.29/W	($6152)	($11 105)	($16 211)
Grid Connection Fee	$3.00/kW	($16 830)	($20 565)	($24 415)
DOE Energy Price Escalation Rate*	None	($13 900)	($18 028)	($22 321)
	40 %	($7558)	($13 310)	($19 176)
O&M Costs	$32.80/W	($12 709)	($17 229)	($21 889)
	$7.42/W	($8 201)	($13 581)	($19 125)
Inverter Replacement Costs	$0.90/W	($14 804)	($18 724)	($22 776)
	$0.42/W	($8450)	($13 873)	($19 458)
Inverter Replacement	15 Years	($6622)	($12 425)	($18 388)
Residual Value[a]	Energy	($2485)	($11 117)	($18 755)
	Proration	($5556)	($13 011)	($19 653)
Federal Tax Credit	30 %	$917	($4037)	($9143)
Loan Financing Percentage	80/20	($12 846)	($14 702)	($15 932)

[a] Net savings for residual value is calculated using the 40 year "No PV Alternative" to keep time frames consistent for the LCCA.

*** The No PV Alternative LCC estimates varies based on the assumed energy price escalation assumptions and discount rate.**

Future costs associated with the solar PV equipment also impact the economic performance of a solar PV system. Incorporating a residual value for the solar PV system (using either method) at the end of the 25-year study period increases net savings from installing the solar PV system to -$5556 or -$2485 assuming a 3.0 % discount rate depending on the method implemented. Variation in the costs of O&M of the solar PV system and inverter replacement period can lead to changes (either positive or negative) in net savings of over $2000 while changes to the inverter replacement costs can swing net savings by up to $4000.

The costs associated with future energy consumption and production can impact net savings. Assuming no energy price escalation over the 25-year study period leads to a reduction of over $3000 in net savings and adding a grid connection fee of $3.00/kW into the electricity cost schedule leads to a reduction in net savings of over $6000 assuming a 3.0 % discount rate.

Table 4-5 summarizes the change in net savings (ΔNS) relative to the baseline solar PV system across the cost-related parameter values. The ΔNS values in Table 4-5 indicate which factors produce the greatest change in the overall LCC assuming a 3 % discount rate. The federal tax credit has the greatest impact on the positive side which is consistent with the results of Table 4-4, and is the only case where the solar PV system is found to be cost effective. An installation cost of $4.96/W produces the worst impact on NS compared to the baseline. In general the life-cycle cost is dominated by the initial costs in this case, with future costs either being small enough or discounted enough to reduce their impacts significantly. These trends are visible across all discount rates. The only exception is the loan financing option. A higher discount rate with the same mortgage APR makes the present value of future costs smaller. In essence the first costs get replaced with annual future costs that have a lower present value. Therefore by increasing or decreasing the discount rate the value of the loan option can go from being a better to a worse option.

Table 4-5 Change in Net Savings Relative to Baseline Solar PV System

		Discount Rate – 3.0 %
Case	**Value**	**Δ Net Savings**
Baseline PV System		0
Installation Costs	$4.69/W	($9996)
	$3.29/W	$4284
Grid Connection Fee	$3.00/kW	($6394)
DOE Energy Price Escalation Rate	None	($3464)
	40 %	$2878
O&M Costs	$32.80/W	($2273)
	$7.42/W	$2234
Inverter Replacement Costs	$0.90/W	($4368)
	$0.42/W	$1986
Inverter Replacement	15 Years	$3813
Residual Value[a]	Energy	$7951
	Proration	$4880
Federal Tax Credit	30 %	$11 353
Loan Financing Percentage	80/20	($2410)

[a] Net savings for residual value is calculated using the 40 year "No PV Alternative" to keep time frames consistent for the LCCA.

In summary, the performance degradation of a solar PV system impacts its economic performance. The degradation rate is more important than the degradation model implemented to estimate future production. There are many other parameters that are more impactful on the economic performance. The most impactful are those that change the upfront cost to the homeowner (installed cost and financial incentives) followed by the discount rate selected and estimated residual value, all of which could be a determining factor in the decision-making process. Variation in energy costs and future costs associated with the solar PV equipment are not as important, but still have a greater impact than the degradation rate. If the initial cost of solar PV systems continue to decline in the future, these other factors as well as the degradation rate could make the difference as to whether a homeowner should install a solar PV system.

5 Conclusion

The economics of residential solar PV systems is rapidly changing. Reductions in PV panel pricing, installation costs, and O&M costs, have eased some of the financial burdens of residential applications. Financial incentive programs (e.g. tax credits, rebates, loans) for solar PV systems vary across the U.S., many of which have expired while others, specifically the 30.0 % federal tax credit, continue to be offered. Indirect system costs such as access fees for connecting residential systems to the electricity grid have been proposed by utilities and, if approved, would change the residential electricity rate structure and the associated economic analysis of installing a solar PV system. Energy prices are expected to increase in the future, but there is minimal certainty in how prices will change over the next few decades. There is also minimal information on the cost of maintaining the performance of a solar PV system, including annual maintenance and periodic replacement of inverters, which have a shorter projected lifespan than solar PV panels.

Other factors beyond direct and indirect costs influence solar PV system cost-effectiveness. Degradation of system modules and its components affect both the energy production and the overall economic performance of PV systems. It is inevitable that the efficiency of a solar PV system will decrease over its useful life, but there is minimal information on the degradation of solar PV systems because most systems have been installed in the last 10 years and may not be considered by homeowners when making investment decisions.

This study considered a number of alternative degradation rates and models to determine the impacts of solar PV performance degradation has on the economic viability of a residential solar PV system installed on the NIST NZERTF, which is a net-zero energy house constructed on the NIST campus in Gaithersburg, MD. These impacts were then compared to those of variations in discount rate and cost-related assumptions.

The degradation rate has a greater impact than the degradation model implemented for the analysis. The sensitivity of solar PV performance can be captured by using a subset of three different specifications tested in this study. A researcher can use a linear degradation rate that reaches the guaranteed performance specified in the system warranty to project the most common degradation prediction approach, a 0 % degradation rate to project the best case scenario of system performance, and either the exponential model or JPL model using the performance guarantee in the system warranty. In the case that the warranty specifies performance at two points in the future (e.g. 5 years and 25 years), the JPL model can be implemented. Otherwise the exponential model can be used because it does not require the additional data point. Use of the JPL model is practical in the case where two degradation rates, or two degraded performance values, are known as it requires two points to define. The JPL model is quicker to diverge from the linear model, resulting in a greater difference for the purposes of sensitivity analysis. In the case where two degradation values are not specified, the exponential model should be used instead because it does not require the additional data point.

Although warranty rates provide a clearer view of how the manufacturer expects the system to perform, they are often specific to company or model, making them ill-suited for use in more general analysis in which the specifics of the solar PV system are unknown. In light of this it makes more sense to use historical degradation rates unless dealing with a specific solar PV system. Note that models and rates for long-term degradation are not as well studied, so care should be taken in applications outside of the typical useful life of a solar PV module.

Assuming linear cumulative degradation and an annual average degradation rate of 0.5 %, a 6.5 % total production loss is realized over a 25-year study period, and leads to an additional $1484 in life-cycle costs from purchasing the 10.2 kW system given a 3 % discount rate. The greatest impacts result from varying the installed costs and incorporating the federal tax credit, as well as increasing the discount rate and including a residual value for the solar PV system into the LCCA. The other parameters, such as the energy rate structure and future solar PV-related equipment costs, all have a greater impact than the PV degradation rate. The solar PV degradation rate does not impact system performance as much as other factors. However, failure to consider the likelihood of efficiency losses can undermine LCC results, and may lead to different decisions on solar PV installation in the future if the installed cost of solar PV systems continues to decline.

Future research should focus on developing a more comprehensive LCCA that includes full probabilistic considerations of potential impacts. Doing so will yield a methodology that can better predict the likelihood that the solar PV system installation will be a more cost-effective alternative to not installing the system. Due to the significant year-over-year decreases in the installed costs of solar PV systems, the analysis should be updated regularly with the most recently collected data in order to best inform homeowners as to the cost-effectiveness of investing in solar PV systems. Additionally, many non-financial factors (e.g. carbon emissions or curb appeal) should be considered in future analysis to understand the role they play in a homeowner's purchase decision. As further advancements in degradation modeling occur and field data on degradation is collected, analyses should be updated so that they consider more accurate degradation measurements and approaches. Including analysis of other financing options, such as leasing or power purchase agreements, would broaden the LCCA's applicability further.

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