NIST Technical Note XXXX

Present Value of Photovoltaics – $[PV]^2$ – User Guide

Joshua Kneifel
David Webb
Luke Donmoyer
Priya Lavappa

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.XXXX

$[PV]^2$
Present Value of Photovoltaics

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

NIST Technical Note XXXX

Present Value of Photovoltaics – $[PV]^2$ – User Guide

Joshua Kneifel
David Webb
Luke Donmoyer

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.XXXX

September 2021

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
James K. Olthoff, Performing the Non-Exclusive Functions and Duties of the Under Secretary of Commerce
for Standards and Technology & Director, National Institute of Standards and Technology

National Institute of Standards and Technology Technical Note XXXX
Natl. Inst. Stand. Technol. Tech. Note XXXX, XX pages (September 2021)
CODEN: NTNOEF

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.XXXX

Abstract

Homeowners are increasing interested in installing solar photovoltaic systems on the roof of their homes. There is a lack of publicly available tools to assist a homeowner in making such an investment decision. The Applied Economic Office (AEO) in Engineering Laboratory (EL) of the National Institute of Standards and Technology (NIST) is addressing this need by developing a free, public web interface that provides independent economic analysis for a specific home based on a user's solar installation quote and electricity bill.

Keywords

Building economics; life cycle costing; life cycle assessment; life cycle impact assessment; residential buildings; commercial buildings; sustainability; green buildings

Preface

This documentation was developed by the Applied Economics Office (AEO) in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). The document explains how the $[PV]^2$ web interface was developed, including the assumptions and data sources. The intended audience is $[PV]^2$ users, solar installers, researchers, and decision makers in the residential building sector, and others interested in residential building sustainability.

Disclaimers

The policy of the National Institute of Standards and Technology is to use metric units in all 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.

Acknowledgements

The $[PV]^2$ tool could not have been completed without the help of others. Thanks are due the NIST Engineering Laboratory (EL) for its support of this work.

The EPA Office of Research and Development, Sustainable Technology Division TRACI team were instrumental in developing the life cycle impact assessment methods incorporated into the tool. The author is particularly grateful for the key cooperation and support offered by a wide variety of feedback from solar installers, homeowners, and industry members.

The authors wish to thank all those who contributed ideas and suggestions for this report. They include XXX and Dr. David Butry of EL's Applied Economics Office, XXX of EL's Energy and Environment Division, and Dr. Nicos S. Martys of EL's Materials and Structural Systems Division.

Author Information

Joshua Kneifel
Economist
National Institute of Standards and Technology
Engineering Laboratory
100 Bureau Drive, Mailstop 8603
Gaithersburg, MD 20899 8603
Tel.: 301-975-6857
Email: joshua.kneifel@nist.gov

David Webb
Engineer
National Institute of Standards and Technology
Engineering Laboratory
100 Bureau Drive, Mailstop 8633
Gaithersburg, MD 20899 8633
Tel.: 301-975-XXXX
Email: brian.polidoro@nist.gov

Luke Donmoyer
Software Engineer
National Institute of Standards and Technology
Engineering Laboratory
100 Bureau Drive, Mailstop 8633
Gaithersburg, MD 20899 8633
Tel.: 301-975-XXXX
Email: brian.polidoro@nist.gov

Contents

List of Figures

List of Tables

List of Acronyms

Acronym	**Definition**
AC	alternating current
ACID	atomicity, consistency, isolation, and durability
AEO	Applied Economics Office
AEO2021	Annual Energy Outlook 2021
AIRR	Adjusted Internal Rate of Return
API	Application Programming Interface
AR5	IPCC Fifth Assessment Report
ASTM	American Society for Testing and Materials
AWS	Amazon Web Services
BCA	benefit-cost analysis
BEES	Building for Environmental and Economic Sustainability
BIRDS	Building Industry Reporting and Design for Sustainability
BIRDS NEST	BIRDS Neutral Environment Software Tool
CED	Cumulative Energy Demand
CFC	chlorofluorocarbons
CFR	Code of Federal Regulations
CO2	carbon dioxide
CPI	Consumer Price Index
CSS	Cascading Style Sheet
CSV	comma-separated values
DC	direct current
DOE	Department of Energy
DSIRE	Database of State Incentives for Renewables & Efficiency
E3	Economic Evaluation Engine
EIA	Energy Information Administration
EL	Engineering Laboratory
ELDST	EL Data, Software, and Technology
EPA	Environmental Protection Agency
EPD	environmental product declaration
EU	European Union
GHG	greenhouse gases
GUI	graphical user interface
GWP	global warming potential
HTML	Hypertext Markup Language
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
LCA	life cycle assessment
LCC	life-cycle cost
LCCA	life-cycle cost analysis

Acronym	**Definition**
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
NOX	nitrous oxides
NREL	National Renewable Energy Laboratory
NS	net savings
O3	ozone
ORM	object-relational mapping
PC	post-consumer
PDF	Portable Document Format
PM2.5	particulate matter less than 2.5 micrometers in diameter
PPA	power purchase agreement
PV	photovoltaic
REST	representational state transfer
RSS	RDF Site Summary or Really Simple Syndication
RV	residual value
SAM	System Advisor Model
SCC	social cost of carbon
SEIA	Solar Energy Industries Association
SO2	sulfur dioxide
SPP	Simple Payback Period
SQL	Structured Query Language
SREC	solar renewable energy credit
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental
VOC	volatile organic compound

1 Introduction to [PV]^2

1.1 Background

Demand for rooftop solar photovoltaic systems has consistently increased over the last decade due to a combination of decreases in installation costs and increased awareness to the implications of climate change and desire to live more sustainably. Figure 1-1 shows that total residential solar systems installed has increase from less than 1000 systems in 2000 to over 300 000 systems each year since 2015 (Barbose, Darghouth, O'Shaughnessy, & Forrester, 2020).

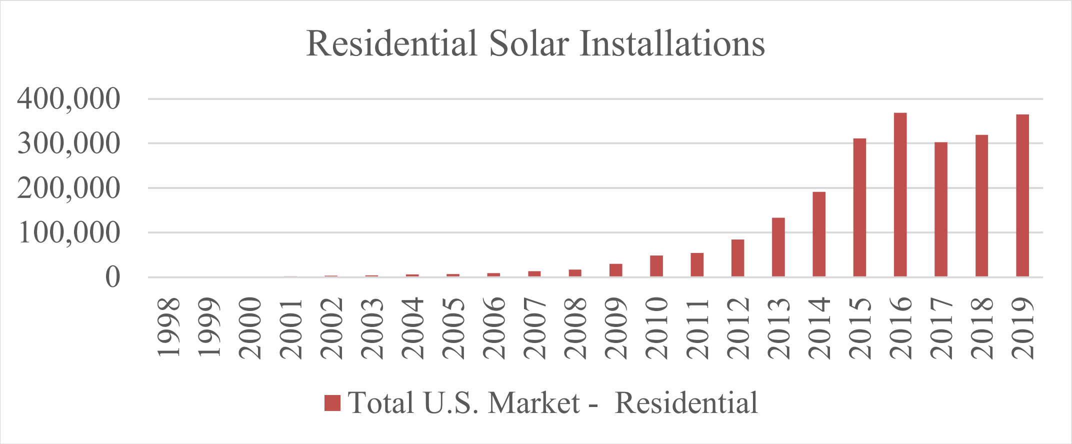
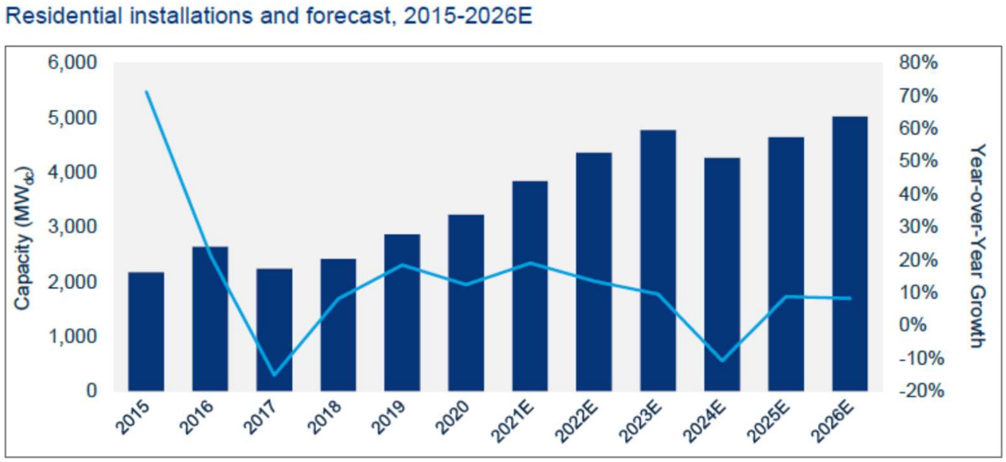


Figure 1-1 Residential Solar Installations (Number of Systems) by Year (1998-2019)

Installations are expected to continue to increase over the next 5 years. Figure 1-2 shows that residential solar photovoltaic capacity installed will increase from approximately 3000 MW_{dc} in 2020 to approximately 5000 MW_{dc} by 2026 (figure obtained from Wood Mackenzie and SEIA (2021)).



Source: Wood Mackenzie; note that Wood Mackenzie's forecasts do not assume any extension of the ITC

Figure 1-2 Actual and Projected Residential Solar Installations (Capacity) by Year (2015-2025)

The key driver of the increased installation has been the reduction in total installed costs of a solar photovoltaic system. Figure 1-3 shows that the median total gross installed cost per watt has decreased from over $12/W to less than $4/W. Most of these reductions were obtained by reducing the cost of the photovoltaic module from over $5/W in 1999 down to $0.44/W in 2019. Inverter costs have decreased from $1.28/W to $0.22/W over the same time frame. The remaining costs, which include the BoS and "soft costs" that include customer acquisition, permitting, and commissioning, have also seen reductions from $5.97/W in 2000 to $2.96/W (Barbose et al., 2020).

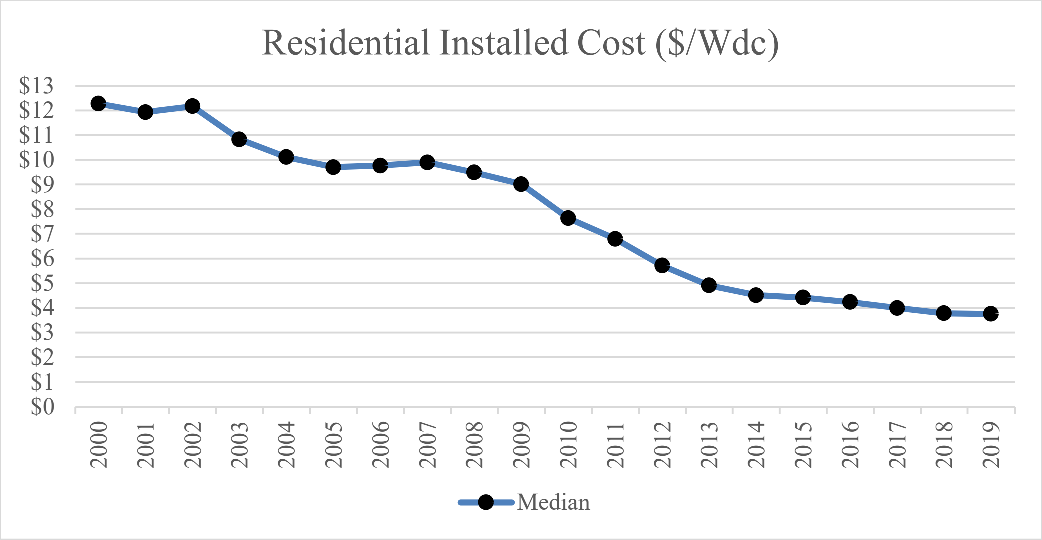


Figure 1-3 Residential Solar Gross Installed Cost Per Watt (2000-2019)

Even as the installed cost has decreased by nearly 70 %, the economic and environmental benefits and costs of installed rooftop solar photovoltaic systems are difficult for the typical homeowner to quantify and evaluate. Each installer may provide different solar technology, brands, and system sizes and configurations. More efficient systems are more costly, but also more productive. Larger systems tend to have a lower average cost per watt because the marginal cost of installing an additional panel is lower once the crew is already on-site. More complex configurations lead to more difficult installations and, therefore higher labor costs. As a result of this variability, a homeowner that receives quotes from more than one installer will find significant installed cost price dispersion and estimated electricity production (and associated future cost savings) from the quoted system. A homeowner must assimilate all this information and select the installer and system design that is optimal for their situation. There are other factors that can influence the economics. For example, each state, county, and/or city may have their own installation and operation requirements as well as provide different financial incentives (Grants, rebates, loan programs, and solar renewable energy credit (SREC) markets).

Solar installers provide some high-level information to the homeowner that can assist in making their decision. The quote typically includes gross installed costs, net installed costs (including available financial incentives), annual and lifetime electricity production, estimated electricity cost savings (based on the homeowner's electricity rates), and lifetime carbon reductions (using a simple emissions factor). However, the information provided does not account for discounting or comparisons to alternative investments. Additionally, solar installers have an incentive to over-estimate the benefits to get an installation contract signed. Homeowners are hesitant to trust the installer estimates, making the decision even more difficult.

1.2 Goal of $[PV]^2$

To assist homeowners in making investment decisions related to solar photovoltaic systems, the Applied Economics Office (AEO) in the Engineering Laboratory (EL) of the National Institute of Standards and Technology (NIST) developed software, called Present Value of PhotoVoltaics – $[PV]^2$, to analyze the economic and environmental implications of installing rooftop solar photovoltaic systems. $[PV]^2$ allows homeowners (and solar installers) to complete an independent, transparent, standards-based life-cycle analysis of a solar installation. Results are provided in easy to understand figures and tables, including clear reporting of assumptions and the ability to download the data for more detailed analysis. The homeowner (or solar installer) need minimal knowledge of life cycle cost or life cycle assessment methodology to interpret the results. Homeowners can be confident that the results from the tool are reliable and transparent, whether completed by the themselves or the solar installer.

Such an independent analysis could be used to answer the following questions, among others:

(1) What are the cost savings of installing a specific system?
(2) How long will it take to recover the initial investment costs of a specific installed system?
(3) What are the environmental benefits of installing a specific system?
(4) Which system option provides the best return on investment?

This technical manual documents the development and assumptions used for of the $[PV]^2$ web application.

1.3 $[PV]^2$ Performance Evaluation Model

The methodology takes a life cycle approach by considering multiple sustainability criteria, economic and environmental impacts, over the entire life of the solar photovoltaic system. All homeowners considering installing a solar photovoltaic system are interested in the economic benefits and costs of their investment decision. Providing a life cycle cost analysis provides a homeowner will a more complete perspective of their investment decision because it looks beyond the first costs to consider operating, maintenance, repair, and replacement costs. Economic performance is measured using the ASTM International standard life cycle cost (LCC) approach (ASTM, 2015).

Homeowners are increasing interested in the environmental implications of their decisions, with particular interest in their carbon footprint. However, there are more environmental impacts from our decisions than climate change, such as ozone depletion and smog creation. Considering multiple impacts across all stages of the life cycle is necessary because decisions based on one criteria or life cycle stage could obscure others that might cause equal or greater damage.

For example, the electricity generation from a solar photovoltaic system produces zero emissions. Each unit of solar-based electricity reduces a unit needed from the electric grid, which current comes from a mix of fuel sources including some percentage of fossil fuels. The result is a reduction in emissions of not just carbon, but also other harmful emission such as particulate matter that can increase asthmatic attacks. However, it is necessary to include environmental impacts resulting from the manufacturing of the solar photovoltaic system as well as the disposal of the system at the end of its service life.

While environmental performance typically cannot be measured on a monetary scale, it can be quantified using the multi-disciplinary approach known as environmental Life Cycle Assessment (LCA) that addresses multiple impact categories over multiple life cycle stages. The BEES methodology measures environmental performance using LCA, following guidance in the International Organization for Standardization (ISO) 14040 and 14044 standards for LCA (International Organization for Standardization (ISO), 2006a, 2006b).

1.4 Information Required by [PV]^2 from the User

[PV]^2 requires minimal information from the user to complete an analysis. The user only needs to provide information on their location, electricity costs, solar photovoltaic system details, costs, and production, available financial incentives, and the state's SREC market. Most installers will request and/or supply this information for their own calculations as part of their solar installation quote.

The homeowner must provide the address of the home on which the solar will be installed. This information is required because the grid-sourced electricity emissions rates vary by location. Each ZIP code is mapped to the Balancing Authority in which it is located. Google Maps is leveraged to assist in populating the address information.

The homeowner must provide their annual electricity consumption and electric utility costs. The consumption can be obtained either from the homeowner's prior year of electricity bills or through their electricity provider's online portal. The electricity costs could be obtained through several approaches. The most accurate approach is to either use the electricity rates on the electricity bills or find the electricity rate schedule for the electricity provider to calculate the fixed costs and variable costs associated with electricity consumption. An easier approach is to assume no fixed costs and use total electricity costs and total electricity consumption to approximate an average cost per unit of electricity. Although this approach is not as accurate, it is unlikely to significantly influence the analysis results. If the homeowner has already provided this information to the solar installer, the information is likely included with the solar installation quote. Other potential data sources are discussed in Section 3.4.

The homeowner must provide the details on the solar photovoltaic system (e.g., rated capacity, inverter technology), gross installed cost of the system, purchasing/financing details, and state/local financial incentives. Financial incentives include grants, rebates, tax credits, and the value of SRECs markets. All this information should be provided with the solar installation quote. Other data sources are discussed in Section 3.4 if a homeowner is using the tool as a cursory analysis before contacting solar installers.

The tool provides default values for the "Advanced" parameter options, such as equipment services lives, energy escalation rates, and solar photovoltaic panel efficiency degradation rate. These underlying assumptions can be viewed and modified by the user. However, changing these values is only recommended for user with a clear understanding of these parameters. Additional details on the advanced parameter default values and data sources is discussed in Section 3.4.

2 User Selections and Parameter Definitions

2.1 Landing Page

A user can access $[PV]^2$ at its landing page: www.nist.pv2.gov. The landing page shown in Figure 2-1 provides the user with a summary description of the tool and a "Start" button to begin an analysis.

PV²

Present Value of PhotoVoltaics (PV^2) is an app that allows homeowners to determine a complete cost of ownership for residential rooftop solar PV systems, helping homeowners make economically wise decisions.

PV^2 uses the E3 API developed at NIST to run an economic analysis of rooftop solar photovoltaics.

Figure 2-1 $[PV]^2$ Landing Page

2.2 Address

The first page of $[PV]^2$ is the "Address" page shown in Figure 2-2 on which the user provides the address (street, city, state, and ZIP code) of the home on which the solar photovoltaic system may be installed. The user should start by typing in the street address and the Google Maps plug-in should auto-populate the city, state, and ZIP code for the user. The ZIP code is used to find the associated environmental data related to electricity consumption in that location. Once the address has been entered, the user can then click on the "Next" button to go to the "Analysis Assumptions" page.

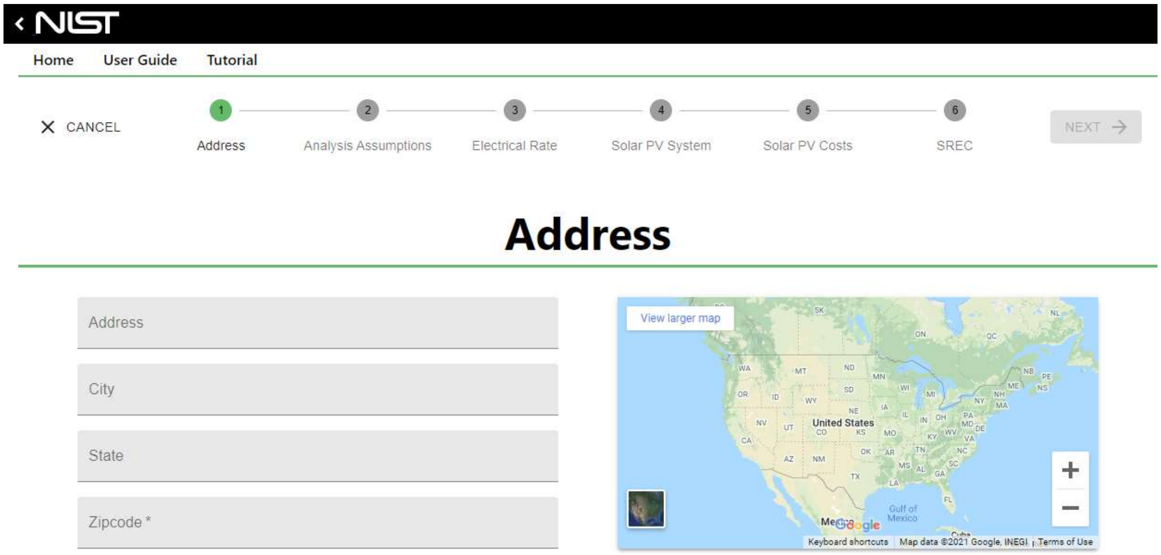
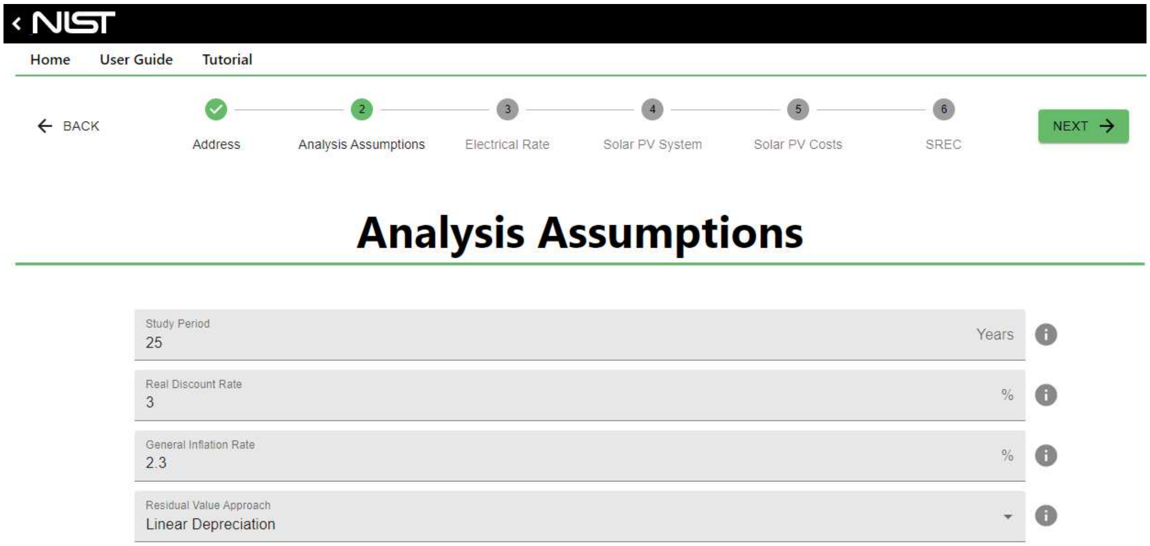


Figure 2-2 Address Page

2.3 Analysis Assumptions

The “Analysis Assumptions” page shown in Figure 2-3 requires the user to input some general economic assumptions: study period, real discount rate, general inflation rate, residual value approach, and electric grid fuel mix. These assumptions are used for completing the economic analysis. Each of these parameters is defined in Table 2-1. Default values are provided for users if they are uncertain what value to input.



Study Period
25 Years

Real Discount Rate
3 %

General Inflation Rate
2.3 %

Residual Value Approach
Linear Depreciation

Figure 2-3 Analysis Assumptions Page

Table 2-1 Analysis Assumptions

Analysis Assumptions	**Definition**	**Valid Values and Unit**
Study period	Study period is the length of the time covered by the economic evaluation	1-40 years
Real discount rate	Real Discount Rate reflects the Time Value of Money apart from changes in the purchasing power of the dollar (i.e., general inflation)	%
General inflation rate	General inflation rate is the rate of rise in the general price level.	%
Residual value approach	Residual Value is the estimated value of the system at the end of the study period	Linear Depreciation Remaining Production Value
Electric Grid Fuel Mix	Electric Grid Fuel Mix is the assumed fuel mix used for the electricity consumed in the building's location	**Benchmark** - current **Projection – Baseline** (AEO2021 Reference case) **Projection – High Renewable** (AEO2021 Low Renewable Cost case)

The study period is the length of the time covered by the economic evaluation and is limited to no more than 40 years. The recommended study period is the estimated service life of the solar photovoltaic system (specifically the solar panels). A common practice is to use the length of the warranty on the solar panels as the study period. Additional information on study periods is provided in Section 3.1.

The real discount rate is the time value of money apart from changes in the purchasing power of the dollar (i.e., general inflation). The basic concept is that a dollar now is worth more to you than a dollar a year from now. There is an opportunity cost for waiting to receive payment of that dollar. The rate of increase in that payment that makes someone indifferent to receiving a dollar now versus that larger payment (dollar plus interest) next year is your discount rate. The real discount rate assumes that the purchasing power of a dollar remains constant. The real discount rate will vary by user and depends on the user's next best alternative investment. For example, the long-term average real rate of return on equities is 7 % (CITE) while investing in 30-year treasury bonds provides a real return of approximately 0 %. In most cases, a user will know their nominal discount rate, which includes inflation. The formula for calculating the real discount rate from the nominal discount rate and general inflation rate is: $d = \frac{1+D}{1+I} - 1$. An example of a nominal discount rate is a user's current mortgage rate if the additional money would otherwise be used to pay down the mortgage balance instead of purchase the solar photovoltaic system. The user would input the nominal discount rate and the inflation rate into the formula to get the real discount rate. Additional information on discount rates is provided in Section 3.3.1.

The general inflation rate is the rate of rise in the general price level, or, put another way, a decline in the general purchasing power of the dollar. The Federal Reserve's target inflation rate for the U.S. is 2.0 %. Additional information inflation is provided in Section 3.3.2.

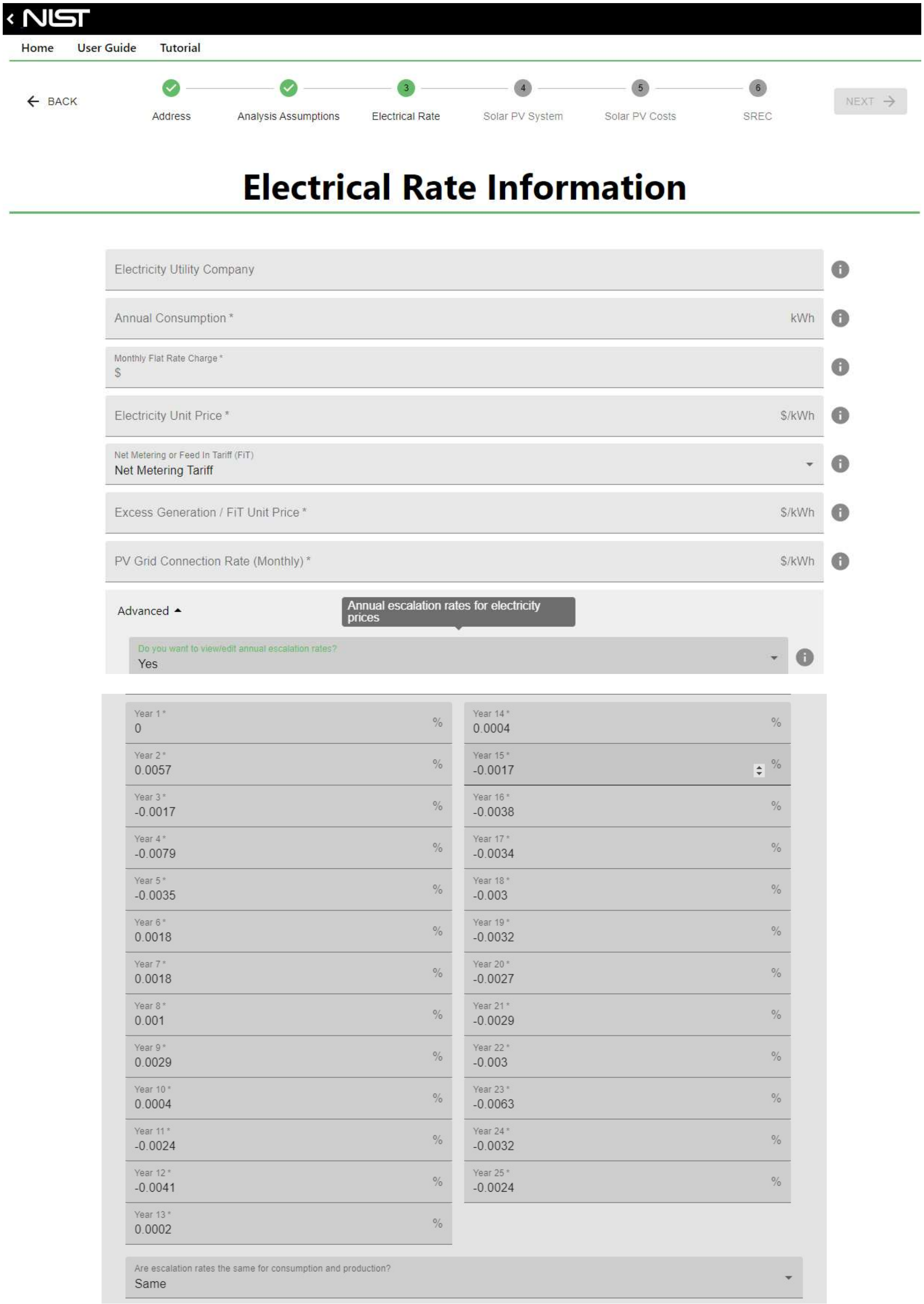
Residual value is the estimated value, of the solar photovoltaic system remaining at the end of the study period, net of any disposal costs. The value could be obtained from resale or salvage of the system or from keeping the system and operational for the remainder of its service life after the study period ends. The linear depreciation approach is the only option currently available for users. This approach assumes that the residual value is a linear function of the installation cost for an investment. Note that if the study period and the service life of the solar photovoltaic system are the same, the residual value will be zero. An alternative approach, Remaining Production Value, will be discussed in Section 3.2.

Electric grid fuel mix is the assumed fuel mix used for the electricity consumed in the building's location, which is mapped to the balancing authority. The fuel mix assumption is used to select the LCA data for electricity in the location. Additional details on the LCA data are discussed in Section 4.5. The three options in [PV]^2:

- **Benchmark** assumes the current electricity fuel mix remains constant over time based on the most recent available data (currently 2018)
- **Projection – Baseline** assumes the electricity fuel mix changes over time based on the AEO2021 Reference case, which has increases in natural gas and renewable capacity over time
- **Projection – High Renewable** assumes the electricity fuel mix changes over time based on the AEO2021 Low Renewable Cost case, which leads to greater renewable energy capacity than the AEO2021 Reference case

2.4 Electrical Rate

The "Electrical Rate" page shown in Figure 2-4 requires the user to input the electric utility name, annual electricity consumption, demand charge, consumption rate, whether its net metering or gross metering, production rate, and photovoltaic grid connection fee. Additionally, the user can view or edit the assumed electricity price escalation rates. These values are used to calculate the electricity costs and savings over the study period. Each of these parameters is defined in Table 2-2. Default values are provided for users if they are uncertain what value to input.



Electrical Rate Information

Electricity Utility Company

Annual Consumption * kWh

Monthly Flat Rate Charge * $

Electricity Unit Price * $/kWh

Net Metering or Feed In Tariff (FiT): Net Metering Tariff

Excess Generation / FiT Unit Price * $/kWh

PV Grid Connection Rate (Monthly) * $/kWh

Do you want to view/edit annual escalation rates? Yes

Year 1 *	0	%	Year 14 *	0.0004	%
Year 2 *	0.0057	%	Year 15 *	-0.0017	%
Year 3 *	-0.0017	%	Year 16 *	-0.0038	%
Year 4 *	-0.0079	%	Year 17 *	-0.0034	%
Year 5 *	-0.0035	%	Year 18 *	-0.003	%
Year 6 *	0.0018	%	Year 19 *	-0.0032	%
Year 7 *	0.0018	%	Year 20 *	-0.0027	%
Year 8 *	0.001	%	Year 21 *	-0.0029	%
Year 9 *	0.0029	%	Year 22 *	-0.003	%
Year 10 *	0.0004	%	Year 23 *	-0.0063	%
Year 11 *	-0.0024	%	Year 24 *	-0.0032	%
Year 12 *	-0.0041	%	Year 25 *	-0.0024	%
Year 13 *	0.0002	%			

Are escalation rates the same for consumption and production? Same

Figure 2-4 Electrical Rate Page

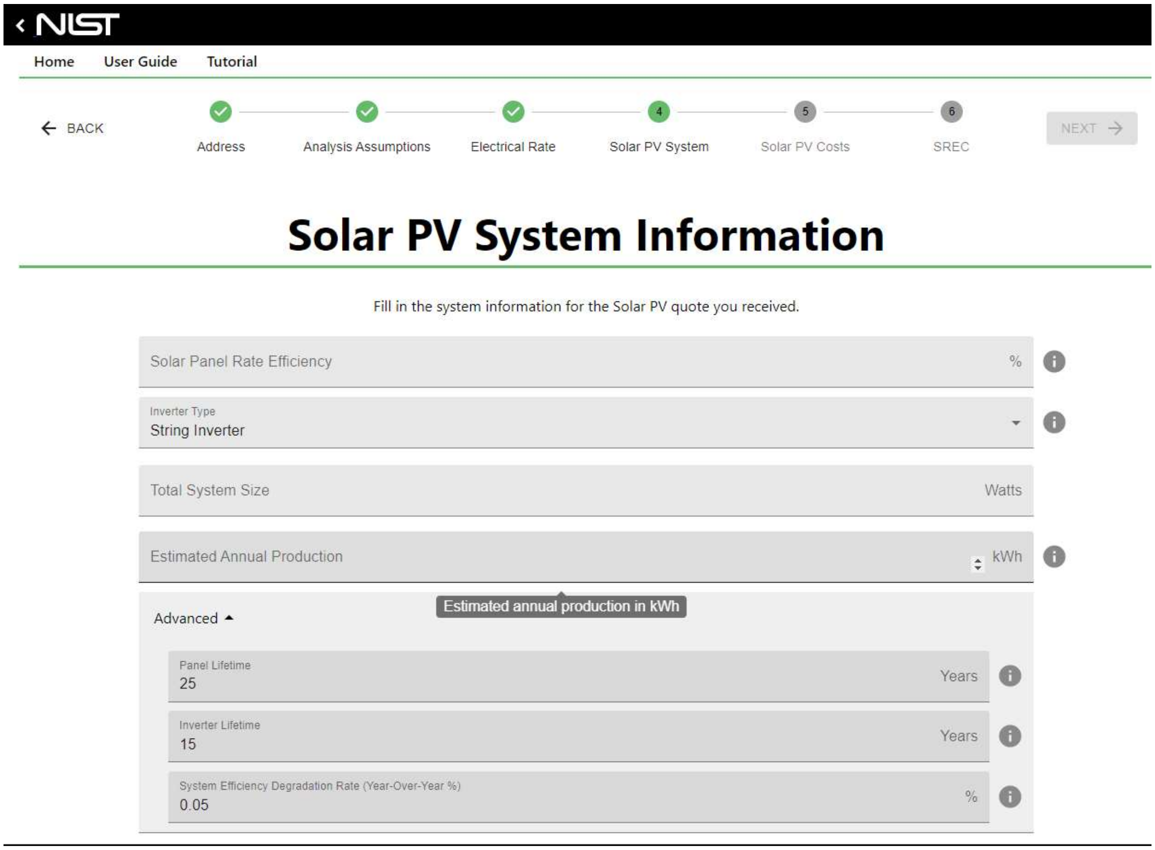
Table 2-2 Electrical Rate

Solar PV System	Information Icon	Unit
Electric Utility Name	Electricity Provider Name.	Not Applicable
Annual Consumption	Annual electricity consumption of the household.	kWh
Demand Charge	Demand charge is a fixed cost for having an electricity provider account.	$
Consumption Rate	Cost per unit of electricity consumed ().	$/kWh
Net or Gross Metering	Net metering means that the homeowner is charged (or paid) for the net difference in electricity consumption and electricity production. Gross metering (i.e., feed in tariff) means that the homeowner is paid for all production and is charged for all consumption, typically at different rates.	Net Metering Gross Metering
Production Rate	Price per unit of electricity produced. Applied to either the net excess production under Net Metering, or to all production under Gross Metering	$/kWh
PV Grid Connection Fee	Annual charge for connecting a solar PV system to the grid. This value is often zero ($0).	$
Annual Escalation Rates (array)	Annual escalation rates for electricity prices.	%

The electricity provider name is currently for informational purposes only. Annual consumption is the annual electricity consumption of the household. A user can use the previous year's bills or obtain consumption data from the users online account for the electricity provider. The demand charge is a fixed cost for having an account and can be found on monthly electricity bills or from the electricity providers rate schedules. Consumption rate is the cost per unit of electricity consumed ($/kWh) is the sum of all costs associated with a unit of electricity (i.e., marginal costs), such as generation, transmission, and distribution charges, taxes, fees, environmental fund payments. Net metering means that the homeowner is charged (or paid) for the net difference in electricity consumption and electricity production. Typically, the price paid for excess consumption is different (usually higher) than the price paid to the homeowner for excess production. Gross metering (i.e., feed-in tariff) means that the homeowner is paid for all production and is charged for all consumption, typically at different rates. Production rate is the price per unit of electricity produced ($/kWh), which is typically different than the consumption price. PV Grid Connection Fee is the annual charge for connecting a solar PV system to the grid. This value is often zero ($0). Annual escalation rates are the rate of change for electricity prices over time. The default values are based on Energy Information Administration (EIA) projections for each Census Region and published in the Annual Supplement to NIST Handbook 135 (add hyperlink). These values are non-constant and are applied to both the consumption rate and production rate. The user can modify the escalation rates.

2.5 Solar PV System

The “Solar PV System” page shown in Figure 2-5 requires the user to input the solar panel rated efficiency, inverter type, system size, and estimated annual production. Additionally, the user can view and modify the panel lifetime, inverter lifetime, and degradation rate. These values are used to calculate the electricity production and associated electricity cost savings, and potential replacement costs and residual value related to the system. Each of these parameters is defined in Table 2-3. Default values are provided for users if they are uncertain what value to input.



Solar PV System Information

Fill in the system information for the Solar PV quote you received.

Solar Panel Rate Efficiency %

Inverter Type: String Inverter

Total System Size Watts

Estimated Annual Production kWh

Estimated annual production in kWh

Advanced

Panel Lifetime: 25 Years

Inverter Lifetime: 15 Years

System Efficiency Degradation Rate (Year-Over-Year %): 0.05 %

Figure 2-5 Solar PV System Page

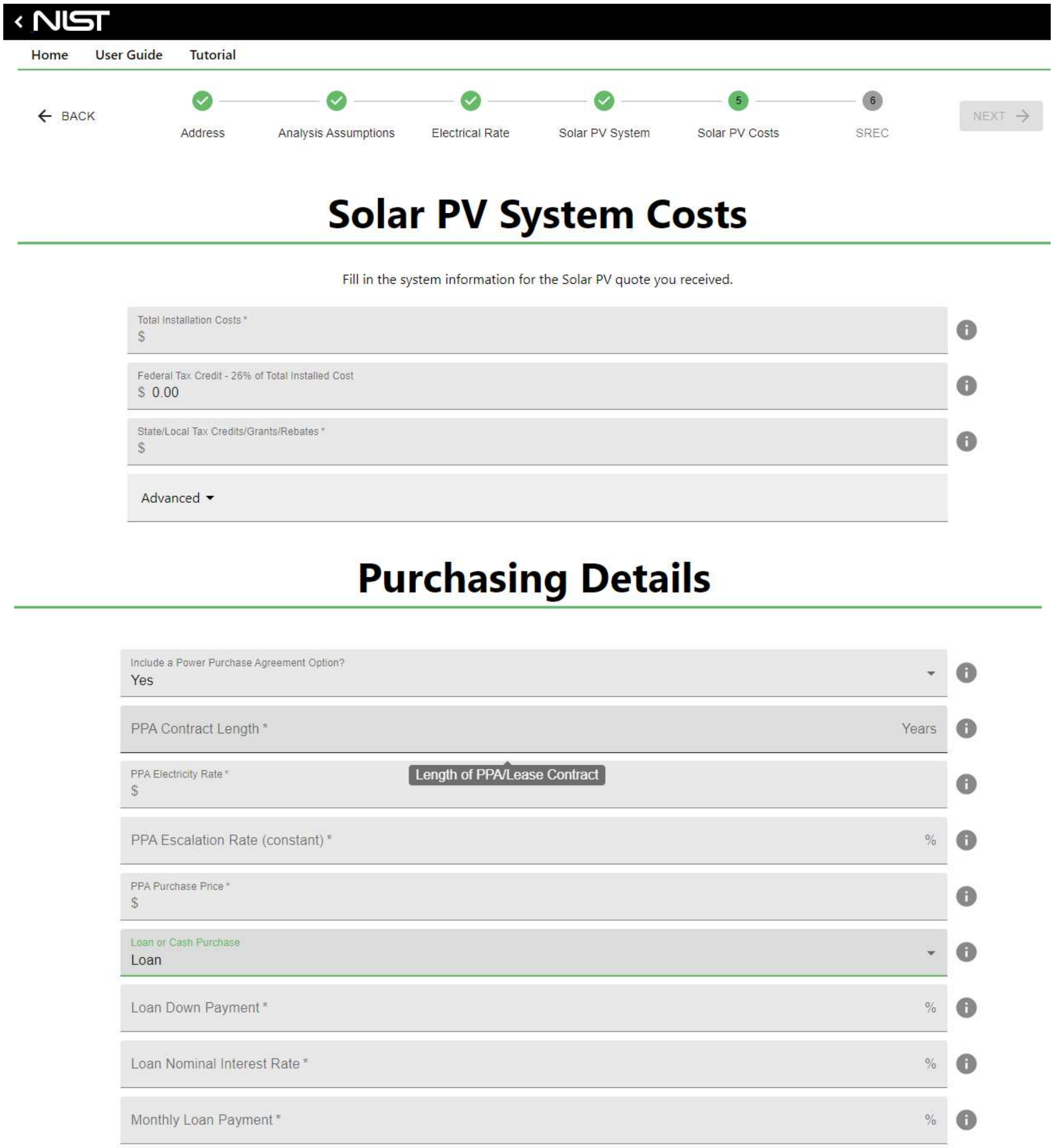
Table 2-3 Solar PV System

Solar PV System	**Information Icon**	**Valid Values and Unit**
Panel Brand / Type	Solar Panel Brand / Type is currently used for informational purposes.	Not Applicable
Solar Panel Rated Efficiency	Solar Panel Rated Efficiency is the rate efficiency on of the solar panels on the panel specification document/installer literature	15-25%
Inverter Type	Inverter technology type: Microinverter, String, or String with Optimizers	Not Applicable
System Size	Total rated capacity of the solar photvoltaic system	W_{dc}
Estimated Annual Production	Estimated annual production in the initial year of operation.	kWh
Panel lifetime	Panel lifetime is the expected service life of the solar panels.	1-40 Years
Inverter lifetime	Inverter lifetime is the expected service life of the inverters.	1-40 Years
Degradation rate	Degradation Rate is the rate at which the solar production decreases each year. Default is 0.5%.	%

The solar panel rated efficiency is used for matching to the solar panel LCA data, which varies by quality category. Solar Panel Rated Efficiency is the rate efficiency on of the solar panels on the panel specification document/installer literature, which will typically range from 16 % - 22 %. The inverter type can be microinverter, string, or string with optimizers. Estimated annual production is the production in the initial year of operation. The calculations in $[PV]^2$ account for decreasing production due to efficiency degradation of the solar photovoltaic system. Panel lifetime is the expected service life of the solar panels, which is typically 25 years (common warranty length) and must be 40 years or less. Inverter lifetime is the expected service life of the inverters and must be 40 years or less. Typical lifetimes by inverter type are 15 years or length of the warranty for string inverters (with or without optimizers) and lifetime or warranty length of panels for microinverters. Degradation rate is the rate at which the solar production decreases each year. The default degradation rate is 0.5%, but specific system degradation should be available in the solar photovoltaic system's warranty document.

2.6 Solar PV Costs

The "Solar PV Costs" page shown in Figure 2-6 requires the user to input solar photovoltaic system cost and purchase details. For system costs, the user must provide the total installation costs and value of state/local financial incentives (grants or rebates). The user has the option to view and modify the inverter replacement costs and annual system maintenance costs. For purchase details, a user must select whether to include a power purchase agreement (PPA) option and the type of purchase (cash or loan). If a PPA option is included, the user must provide the PPA contract length, electricity rate, electricity escalation rate, and system purchase price at the end of the contract. If the purchase type is a loan, the user must provide the down payment and nominal interest rate, which are used to calculate the monthly payments. Alternatively, the user can also provide the monthly payment directly, which is commonly provided in the solar installer quote. Each of these parameters is defined in Table 2-4. Default values are provided for users if they are uncertain what value to input.



Solar PV System Costs

Fill in the system information for the Solar PV quote you received.

Total Installation Costs *
$

Federal Tax Credit - 26% of Total Installed Cost
$ 0.00

State/Local Tax Credits/Grants/Rebates *
$

Purchasing Details

Include a Power Purchase Agreement Option?
Yes

PPA Contract Length * Years

PPA Electricity Rate *
$

PPA Escalation Rate (constant) * %

PPA Purchase Price *
$

Loan or Cash Purchase
Loan

Loan Down Payment * %

Loan Nominal Interest Rate * %

Monthly Loan Payment * %

Figure 2-6 Solar PV Costs Page

Table 2-4 Solar PV Costs

Solar PV System	Information Icon	Valid Values and Unit
Total Installation Costs	Total (gross) costs of installing the system.	$
Fed Tax Credit	Federal tax credit is currently 26% of total installation costs.	$
State/Local Grants/Rebates	State and local financial incentives include grant and rebate programs.	$
Inverter replacement costs	Costs of replacing only the inverters.	$
Annual maintenance costs	Annual costs of maintaining the solar PV system	$
PPA Option	Include a PPA/leasing option in the analysis.	YES / NO
PPA Contract Length	Length of PPA/Lease Contract. 40 years or less.	1-40 Years
PPA Electricity Rate	Price of electricity produced by solar PV system.	$
PPA Escalation Rate (constant)	Rate at which the price of electricity from solar PV system increases year-over-year.	%
PPA Purchase Price	Cost to purchase system at the end of the contract.	$
Loan or Cash	Choose between purchasing upfront (“cash”) or through financing (loan).	Not Applicable
Down payment	Percent of Total Installed Cost Paid at Time of Signature/Installation.	$
Nominal interest rate	Nominal interest rate on the loan.	%
Monthly payment (optional)	Monthly payment on the loan.	$

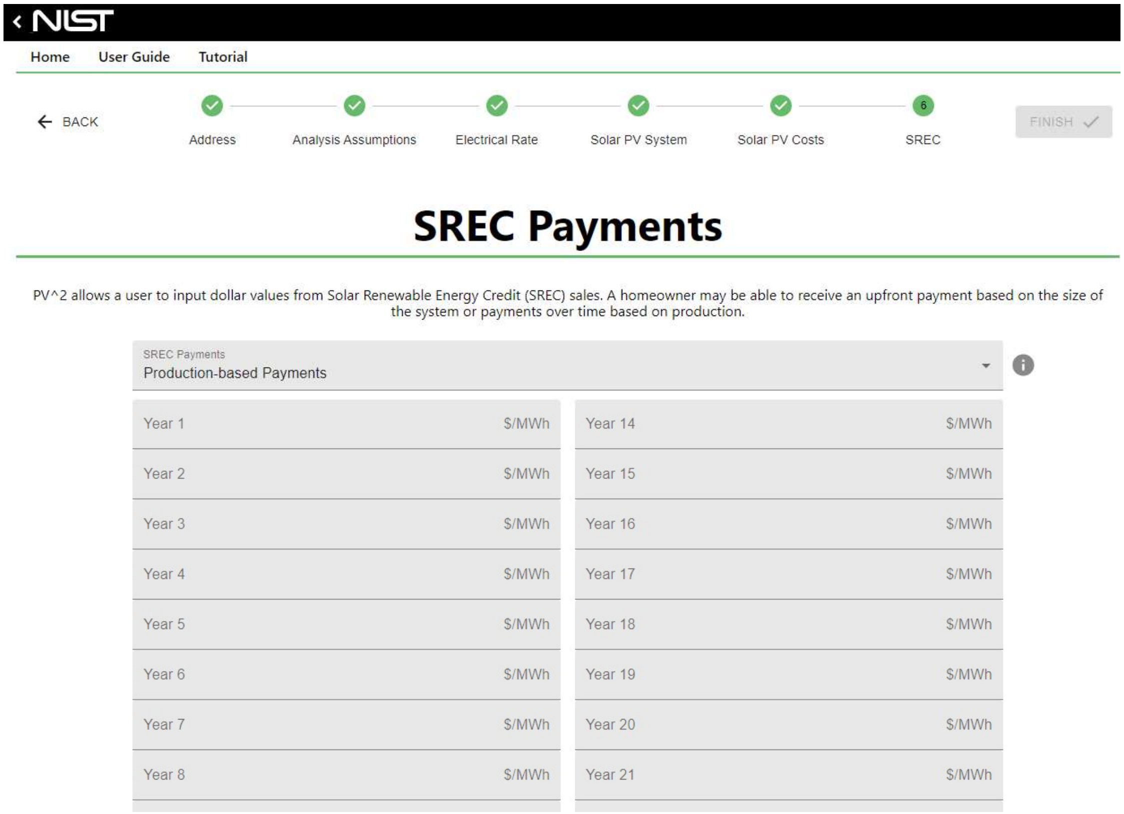
Total installation costs are the total (gross) costs of installing the system before financial incentives, such as federal tax credits and state/local grants or rebates. The user should exclude any costs for re-roofing because that is treated as an independent decision. The federal tax credit is currently 26% of total installation costs. This credit applies to all costs associated with the installation. The value is automatically calculated by $[PV]^2$ using the tax credit rate and the total installation costs, but can be modified by the user. State and local financial incentives include grant and rebate programs. These should be summed and included as a single value. Loan programs will be addressed under Purchasing Details below. Inverter replacement costs are the costs of replacing only the inverters. The value should only be provided if the inverter’s expected service life is not the same as the solar panels. Annual maintenance costs are the annual costs of maintaining the solar PV system, such as annual contract with installer to clean panels and check panel performance. These costs tend to be minimal.

In the case that a solar photovoltaic system installed through a PPA or lease, the installer owns the system and homeowners sign a contract to pay the installer for the electricity produced by the system. Typically, homeowners have a purchase option at the end of the contract, which can vary in length, but typically will not extend beyond 25 years and is limited to 40 years or less in $[PV]^2$. PPA electricity rate is the price of electricity produced by solar photovoltaic system under the PPA. Typically, this price is less than price paid to electricity provider for grid-sources electricity. PPA escalation rate is the rate at which the price of electricity from solar PV system increases year-over-year, which is assumed to be constant. The PPA purchase price is the cost to purchase system at the end of the contract. If purchased, all production from the photovoltaic system after the end of the contract through the end of the study period is owned by the homeowner.

The cash or loan decision is a choice between purchasing upfront ("cash") or through financing (loan). In the case of a loan, the down payment is the percent of total installed cost paid at the time of signature or installation. Down payments typically range from 0 % to 20 %. The nominal interest rate is the interest rate paid on the loan while the monthly payment is the amount paid each month on the loan.

2.7 SREC

The "SREC" page shown in Figure 2-7 requires the user to select the type of SREC payment and the value of those payments. These may include a single up-front payment or future payments based on production. Each of these parameters is defined in Table 2-5. Values are defaulted to zero.



SREC Payments

PV^2 allows a user to input dollar values from Solar Renewable Energy Credit (SREC) sales. A homeowner may be able to receive an upfront payment based on the size of the system or payments over time based on production.

SREC Payments: Production-based Payments

Year 1	$/MWh	Year 14	$/MWh
Year 2	$/MWh	Year 15	$/MWh
Year 3	$/MWh	Year 16	$/MWh
Year 4	$/MWh	Year 17	$/MWh
Year 5	$/MWh	Year 18	$/MWh
Year 6	$/MWh	Year 19	$/MWh
Year 7	$/MWh	Year 20	$/MWh
Year 8	$/MWh	Year 21	$/MWh

Figure 2-7 SREC Page

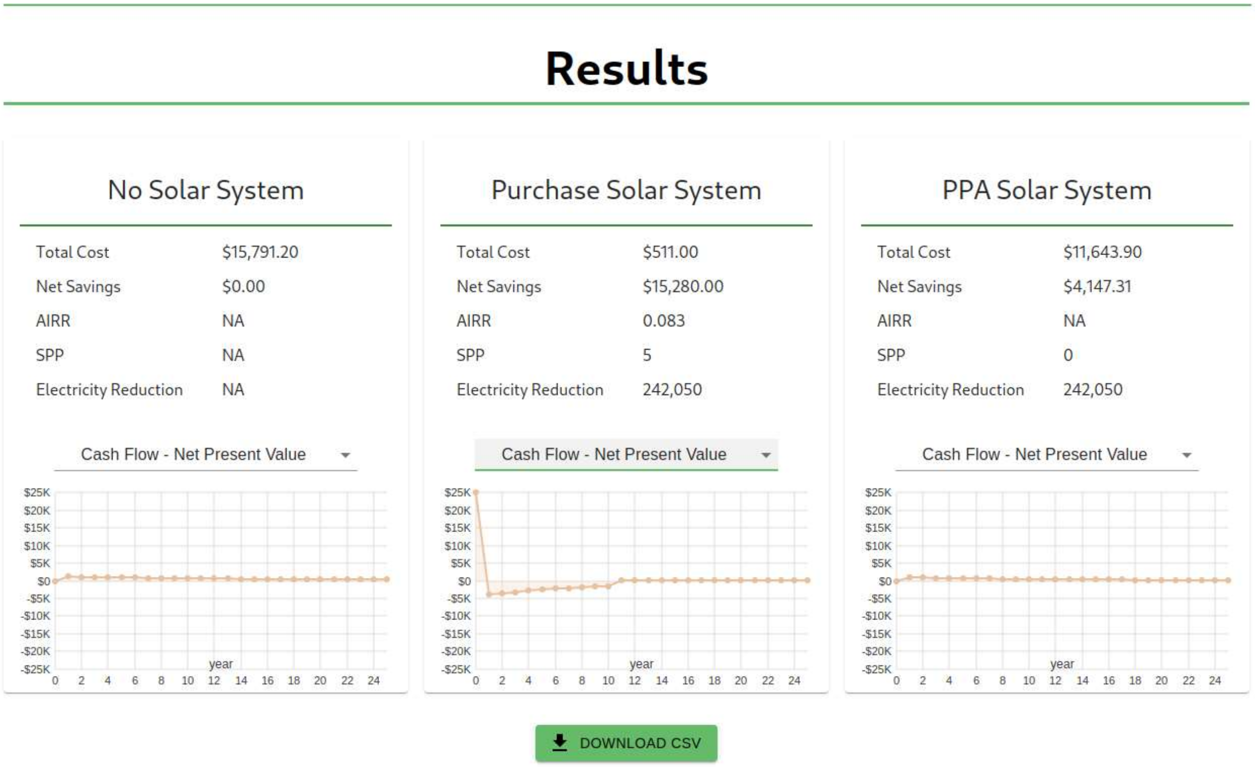
Table 2-5 SRECs

SRECs	Information Icon	Valid Values and Units
Upfront Payment or Production Based Payments	Choose how the homeowner wants to get paid for their SRECs: upfront lump sum based on capacity or over time based on production	
Upfront payment	An upfront payment is a one-time lump sum value paid to the homeowner for the rights to all SRECs.	$/kW
Payment by Year of Study Period	Payments over time are based on actual or estimated production by the solar PV system.	$/MWh

Solar Renewable Energy Credits (SRECs) are not available in all states. Therefore, there will be no value to a homeowner in most states. If an SREC market does exist in a user's location, then there are typically two options for monetizing those values, either through up-front or future payments. Selecting an up-front payment means the rights to the SRECs are sold upfront in a lump sum value based on rated capacity ($/kW). Selecting production-based payments means that payments are made every 3 months based on production from the system ($/MWh). The user must provide the expected value of future SREC payments for each year of the study period. There is variability and uncertainty in the expected value of SRECs in the future as well as actual production. Therefore, SREC aggregators provide production-based contract for 3-10 years that guarantee a value of those SRECs (at a discount to current SREC market prices).

2.8 Results

The "Results" page shown in Figure 2-8 provides the user with the economic and environmental performance of two alternatives (or three alternatives if a PPA option was included). The economic measures provided are total cost, net savings, adjusted internal rate of return (AIRR), and simple payback period (SPP). The electricity reduction measures include total electricity reduction and fraction of electricity consumption offset. The environmental measures include global warming potential (GWP), total primary energy consumption, ozone depletion, smog creation, acidification, eutrophication, and respiratory effects. Each of these measures are defined in Table 2-6. The figures allow a user to view net present value by year for annual cash flows, annual net savings, and cumulative net savings.



Results

No Solar System

Total Cost	$15,791.20
Net Savings	$0.00
AIRR	NA
SPP	NA
Electricity Reduction	NA

Cash Flow - Net Present Value

Purchase Solar System

Total Cost	$511.00
Net Savings	$15,280.00
AIRR	0.083
SPP	5
Electricity Reduction	242,050

Cash Flow - Net Present Value

PPA Solar System

Total Cost	$11,643.90
Net Savings	$4,147.31
AIRR	NA
SPP	0
Electricity Reduction	242,050

Cash Flow - Net Present Value

Figure 2-8 Results Page

Table 2-6 Results

Results	Description	Valid Values and Units
Total Cost	Total Net Present Value Costs	$
Net Savings	Net savings (NS) is Net Present Value Cost Savings relative to No Solar System	$
AIRR	Adjusted Internal Rate of Return (AIRR) on Investment	%
SPP	Simple Payback Period (SPP)	Years
Electricity Reduction	Electricity reduction relative to No Solar System	kWh
Percent Electricity Reduction	Percent reduction in electricity consumption relative to No Solar System	%
Externality Costs – Social Cost of Carbon	The Social Cost of Carbon is the negative impact, in dollar terms, of greenhouse gas (GHG) emissions	$
GWP	Global Warming Potential	CO2e
Total Primary Energy	Total primary energy consumption	MJ
Respiratory Effects	Respiratory effects	PM2.5e
Ozone Depletion	Ozone Depletion	CFC-11e
Smog	Smog formation	O3
Acidification	Acidification potential	SO2e
Eutrophication	Eutrophication potential	Ne

Total Cost is the Total Net Present Value Costs for the alternative over the study period. If the net present value of the total costs is lower for an alternative relative to the baseline alternative, then that alternative is preferred to the baseline. Net Savings is the Total Net Present Value Savings relative to the baseline alternative (i.e., No Solar System). If the present value of net savings is positive for an alternative, then that alternative is preferred to the baseline. Adjusted Internal Rate of Return (AIRR) is a measure of the return on investment that accounts for reinvestment of the annual savings at the real reinvestment rate, which is set equal to the real discount rate in [PV][2]. Simple Payback Period (SPP) is the number of years it takes for nominal cumulative cost savings to offset the initial investment costs, or how many years does it take to recoup the initial investment.

Electricity Reduction is the total amount of electricity consumption (kWh) from the electric grid that is avoided relative to baseline alternative (No Solar System). Percent electricity reduction is the percent reduction in electricity consumption relative to No Solar System. A value of 100 % means that the solar photovoltaic system meets electricity consumption demand over the study period (i.e., net zero electricity demand).

The environmental and social performance is measured with seven life cycle impact assessment categories. The three categories of most interest to current decision makers are GWP, total primary energy consumption, and respiratory effects. GWP is used to measure the climate change-related impacts. Total primary energy consumption includes all energy associated with both the grid-based electricity reduced as well as the embodied energy in the solar photovoltaic system. The broader perspective on energy consumption provides a more complete perspective on the life cycle implications of installing sola photovoltaics. Respiratory effects measure particulate matter and air emissions that may result in health issues such as asthma and other respiratory illnesses. The other four impact categories are ozone depletion, smog formation, acidification potential, and eutrophication potential. All impact categories are discussed in more detail in Section 4.3.

The social cost of carbon (SCC) is the estimate negative impact, in dollar terms, of greenhouse gas (GHG) emissions on society. The value is set to $51/ton of emissions and applied to all GHG emissions as measured in the GWP impact category (includes embodied emissions in the solar photovoltaic system and the reduction in grid-provided electricity consumption). SCC is discussed in more detail in Section 3.5.1.

Along with the summary results provided in tables and figures, the user can print the summary results and/or download the data to develop their own data analysis that the current tool does not provide. For example, the user may want to compare the relative performance of two different solar photovoltaic systems. If the baseline case is the same, a user can either manually compare the results across printed results or create their own system comparison in a spreadsheet.

3 Economic Performance Evaluation

Measuring the economic performance of solar photovoltaic systems is relatively straightforward. Cost data are readily available from the solar installer and the electricity provider, and there are well-established ASTM standard methods for conducting economic performance evaluations. The most appropriate method for measuring the economic performance of building products is the life cycle cost (LCC) method (Joshua Kneifel & Webb, 2020). $[PV]^2$ follows the ASTM standard method for life cycle costing of building-related investments (ASTM, 2017).

3.1 Study Period

It is important to distinguish between the time periods used to measure environmental performance and economic performance. These time periods are different. Recall that in environmental LCA, the time period begins with raw material acquisition and ends with product end-of-life. Economic performance, on the other hand, is evaluated over a fixed period (known as the study period) that begins with the purchase and installation of the product and ends at some point in the future that does not necessarily correspond with product end-of-life.

Economic performance is evaluated beginning at product purchase and installation because this is when out-of-pocket costs begin to be incurred, and investment decisions are made based upon out-of-pocket costs. The study period ends at a fixed date in the future, which could vary based on the homeowner’s expected number of years owning the home. If the homeowner expects to sell the home before the end of solar photovoltaic system’s service life, the study period length could be set at the period of home ownership. If the homeowner expects to be a long-term owner of the home, the study period length could be set at the useful life of the longest-lived product alternative (i.e., solar panel service life).

In $[PV]^2$, economic performance is measured over a study period defined by the user up to 40 years. Solar photovoltaic panels typically have a warrantee of up to 25 years. However, as more long-term installation performance data have become available, some installers are beginning to claim the potential for a 40-year service life. Additionally, there are no available projections for energy prices beyond 40 years into the future. Therefore, the maximum study period allowed is 40 years.

3.2 Life Cycle Costing

The LCC method sums over the study period all relevant costs associated with each alternative to meet the household’s electricity demand. Alternatives can then be compared based on their LCCs to determine which is the least cost means of fulfilling the electricity demand over the study period. Categories of cost typically include costs for purchase, installation, operation, maintenance, repair, and replacement. The costs associated with the initial purchase and installation and any replacements that occur over the study period are based on the defined system service life. The cost of equipment replacements is assumed to be the same as the initial purchase and installation costs. Annual maintenance costs are assumed to ensure no repair costs occur. The residual value is the value of the product remaining at the end of the study period and is, therefore, a negative cost value.

In [PV]^2, the residual value is computed for the last equipment installation by prorating the purchase and installation cost over the product life remaining beyond the 60-year period (linear depreciation approach). An alternative residual value approach is the estimated value of the electricity production from the remaining life of the solar photovoltaic system.

The total LCC of an alternative (C_{LCC}) is the sum of the present values of first cost (C_{First}) and future costs (C_{Future}) minus the residual value (RV) as shown in the following equation:

$$C_{LCC} = C_{First} + C_{Future} - RV$$

Where C_{First} = *Costs of initial purchase and installation*
C_{Future} = *Present Value of replacement costs*
RV = *Residual Value of last product installation*

3.3 Discount Rate and Inflation

The LCC method accounts for the time value of money by using a discount rate to convert all future costs to their equivalent present value. Future costs must be expressed in terms consistent with the discount rate. There are two approaches. First, a *real* discount rate may be used with constant-dollar costs. Real discount rates reflect the portion of the time value of money attributable to the real earning power of money over time and not to general price inflation. Even if all future costs are expressed in constant dollars, they must be discounted to reflect this portion of the time-value of money. Second, a *market (nominal)* discount rate may be used with current-dollar amounts (e.g., actual future prices). Market discount rates reflect the time value of money stemming from both inflation and the real earning power of money over time. When applied properly, both approaches yield the same LCC results. The [PV]^2 model computes LCCs using constant dollars and a real discount rate. This section provides background on potential discount rate and inflation rate values and how the default values were selected.

3.3.1 Discount Rate

As a default, [PV]^2 offers a real rate of 3.0 %, the 2021 real discount rate for DOE energy efficiency, water conservation, and renewable energy project evaluation (Lavappa & Kneifel, 2021) and the “social rate of time preference” (OIRA, 2011; OMB, 2003).

Lavappa and Kneifel (2021) sets the real discount rate at 3 % based on the process defined in 10 Code of Federal Regulations (CFR) 436, which is the higher of two values: (1) The real discount rate calculated using long-term Treasury Bond rates averaged over 12 months and the general inflation rate published in the Report of the President’s Economic Advisors, Analytical Perspectives (OMB, 2017) or (2) a prescribed floor of 3 %. The calculated real discount rate has been lower than the prescribed floor of 3 % for the past 10+ years.

Circular A-4 assumes that "the rate that the average saver uses to discount future consumption is a measure of the social rate of time preference, the real rate of return on long-term government debt may provide a fair approximation" and determines the 3 % real discount rate based on the average real annual terms on a pre-tax basis for 1973 to 2003 (OMB, 2003).

Given that the 3 % discount rates using either Circular A-4 or 10 CFR 436 are based on either dated data (15+ years old) or a prescribed floor that does not capture the current economic conditions, it may be appropriate to select an alternative discount rate. For example, Appendix C of Circular A-94 (OMB, 1992) is updated annually to specify the real discount rates applicable to general capital investments based on Treasury Notes and Bonds with maturities from 3 years to 30 years. For 2021, those rates vary from – 1.8 % for 3 years to -0.3 % for 30 years (Lavappa & Kneifel, 2021). After accounting for inflation, real discount rates may be near or below 0.0 % depending on the study period.

Another alternative is the "historical average before-tax rate of return to private capital in the U.S. economy," which Circular A-4 estimates to be 7.0 % (OMB, 2003). This value is consistent with what has been termed at "Siegel's Constant" of real returns from the stock market of 6.5 % (Wright et al., 2011).

Circular A-4 also recommends a lower discount rate in the case of longer-term decision-making that includes intergenerational impacts, in which case "the agency might consider a sensitivity analysis using a lower but positive discount rate, ranging from 1 percent to 3 percent, in addition to calculating net benefits using discount rates of 3 percent and 7 percent" (OIRA, 2011).

The approaches thus far have been focused on financial markets (i.e., stocks and bonds). Another approach to estimate a discount rate is to develop an implied social discount rate using time preference, risk/inequality aversion, and expected growth rate using the Ramsey Rule (NAS, 2017). The literature using this approach have estimates of the implied long-term social discount rate ranging from 1.4 % to 6.0 % depending on the study (NAS, 2017).

Aggregated average discount rates discussed above range from -0.5 % to 7.0 %. However, a $[PV]^2$ user may have a different personal real discount rate than the estimated or prescribed social or economy-wide discount rates because personal preferences can vary significantly from person to person. Studies have found some real personal discount rates can vary from 0 % to 30 % with many finding average personal discount rates higher than 7.0 % depending on the specific demographics, magnitude of the trade-off values, and topic and approach in the study (Alberini & Chiabai, 2007; Cameron & Gerdes, 2002; Moore & Viscusi, 1990; Scharff & Viscusi, 2011; Warner & Pleeter, 2001). Therefore, it is important for the users to consider the purpose of the analysis and select an appropriate discount rate.

3.3.2 Inflation Rate

The default inflation rate is set based on the average inflation rate projected for the next 10 years (2.3 %) published in the most recent Report of the President's Economic Advisors, Analytical Perspectives (CITE). As with the discount rate, a user should consider whether this inflation rate is appropriate for their expectations. Since 2010, the inflation rate has varied from year to year between 0 % and 3 %. However, short-term inflation rates in 2021 have risen significantly and there is uncertainty as to whether these inflation rates will subside or continue in the near future. A common data source for finding inflation rates is the Consumer Price Indices (CPI), which can be obtained here: https://www.bls.gov/regions/subjects/consumer-price-indexes.htm.

3.4 Economic Data

Most of the economic data required to complete the economic analysis are available from the solar installer and/or the electricity provider, whether it's the costs associated with the solar installation, electricity consumption and costs, or available financial incentives. In cases where the required information is not available from the solar installer or electricity provider, the user can use the following sources:

- Installed costs for solar photovoltaic systems can be obtained from several different sources
    - Quoted installed cost data for different states and brands can be obtained from EnergySage: https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/.
    - Reported installed cost data for different states, efficiencies, and technologies can be obtained from Lawrence Berkeley Laboratory's Tracking the Sun: https://emp.lbl.gov/tracking-the-sun
- Local and state financial incentives are available from Database of State Incentives for Renewables & Efficiency (DSIRE) USA: https://www.dsireusa.org/.
- State SREC markets and credit prices can be found at SRECTrade: https://www.srectrade.com/.
- SREC contract options are available from SREC aggregators such as SolSystems: https://www.solsystems.com/srec-services/state-srec-markets/).
- State average electricity price can be obtained from the EIA: https://www.eia.gov/electricity/data.php#revenue under "Sales (consumption), revenue, prices & customers" > "Average retail price of electricity to ultimate customers."

Default data for the "Advanced" options are as follows:

- Energy escalation rates are defaulted to values from Lavappa and Kneifel (2021) that are based on energy price projections at the Census Region level from the EIA.
- Annual maintenance costs are defaulted to $0.03/W based on values from Webb, Kneifel, and O'Fallon (2020), which represent annual equipment check-up and cleaning.

- Solar panel lifetime is defaulted to 25 years (CITE)
- Inverter lifetime is defaulted to one of two values
    - String Inverters - 12 years for string inverters (Webb et al., 2020)
    - Microinverters/Optimizers - Equal to the solar panel lifetime; microinverters/optimizers are part of the solar panel and have the same warranty
- Replacement costs for string inverters is defaulted to $0.18 (Webb et al., 2020); only used for string inverters
- System efficiency degradation rate is defaulted to 0.5 % (J Kneifel, Webb, & O'Rear, 2016); solar panel equipment specification sheets typically provide expected degradation rates (often available from solar installer)

Although these values are based on reliable sources, one or more of the values may not be appropriate for a specific user's analyses. Users can modify these values as they deem appropriate.

Note: Electricity rates may vary by season. In such a case, an average of the prices in different seasons weighted by consumption in those seasons is preferred. In a few instances, electricity providers provide "real-time" pricing that varies throughout the day. This pricing schedule cannot be accounted for in $[PV]^2$.

3.5 Externality Costs

Externalities are an impact that affects other parties that are not reflected in the cost of a product. In this case, it is an impact that is not included in the economic analysis. An externality can be included in the economic analysis if those externalities can be monetized. $[PV]^2$ does not include any externalities in the economic analysis but does provide an externality cost for GWP as a separate reported economic measure. GWP is also reported using LCIA measures, as are other impact categories that are more difficult, or possibly impossible, to monetize.

3.5.1 Social Cost of Carbon

$[PV]^2$ currently uses a fixed price for the social cost of carbon, $51/metric ton, which is based on emissions in 2020 assuming a 3 % discount rate (United States Government, 2021). All GHG emissions measured by the GWP impact category (CO_2e emissions) are included regardless of whether the emissions are embodied in the solar photovoltaic system or the grid-based electricity. However, the SCC has been projected to rise over time. Future versions of $[PV]^2$ could introduce time varying prices if deemed beneficial to users.

United States Government (2021) provides distributions of SCC estimates (2020 US dollars) assuming different discount rates: 5 %, 3 %, and 2.5 %. Table 3-1 shows the average SCC values for each discount rate in 5-year increments. A 4th value, the 95th percentile value for the 3 % discount rate case is an example of a high SCC scenario. The estimate distributions have a left-skewed distribution with long right tails. Please see United States Government (2021) for more detailed information on these distributions.

Table 3-1 Social Cost of Carbon Estimates

SCC Per Metric Ton (2020 US dollars)				
Year	**Average Price**			**95th Pct**
	5%	**3%**	**2.5%**	**3%**
2020	$14	**$51**	$76	$152
2025	$17	$56	$83	$169
2030	$19	$62	$89	$187
2035	$22	$67	$96	$206
2040	$25	$73	$103	$225
2045	$28	$79	$110	$242
2050	$32	$85	$116	$260

3.5.2 Cost of Respiratory Effects

The cost of respiratory effects is not currently included in [PV]^2. The cost of respiratory effects could be a potential expansion into other externalities in the future.

4 Environmental Performance Evaluation

The LCAs for the solar photovoltaic equipment and grid-based electricity consumption have been conducted in accordance with the requirements of the ISO 14040 and 14044 standards for LCA (International Organization for Standardization (ISO), 2006a, 2006b). Environmental LCA is a "cradle-to-grave," systems approach for measuring environmental performance. The approach is based on the logic that all stages in the life of a product generate environmental impacts and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste management. An analysis that excludes any of these stages – without explicit rationale for doing so – is limited because it ignores the full range of upstream and downstream impacts of stage-specific processes.

The strength of LCA is its comprehensive, multi-dimensional scope. Some green product claims and strategies are based on a single life cycle stage or a single environmental impact. A product may be claimed to be green simply because it has recycled content or accused of not being green because it emits volatile organic compounds (VOCs) during its installation and use. These single-attribute claims may be misleading because they ignore the possibility that other life cycle stages, or other environmental impacts, may yield offsetting effects. For example, a product with recycled content may have a high embodied fuel content, leading to fossil fuel depletion, GWP, and acid rain impacts during the raw materials acquisition, manufacturing, and transportation life cycle stages. LCA thus broadens the environmental discussion by accounting for potential shifts of environmental problems from one life cycle stage to another, or one environmental medium (land, air, water) to another. The benefit of the LCA approach is in implementing a trade-off analysis to assess where in the life cycle overall impacts may be reduced, rather than limiting the scope to a shift of impact.

The general LCA methodology involves four steps (International Organization for Standardization (ISO), 2006a, 2006b).

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

The goal and scope definition step outlines the purpose of the study and its breadth and depth. The inventory analysis step identifies and quantifies the environmental inputs and outputs associated with a building product over its entire life cycle. The quantification and aggregation of results is called the LCI, which includes elementary flow inputs (i.e., resources from the earth, such as water, fossil fuels, minerals). Elementary flow outputs include releases to air, land, and water. The LCI output is large, and it is difficult to assign meaning to its individual elements. Nonetheless, we are interested in the LCI flows' consequences, or how they may potentially impact the environment and human health, and this determination is done in the impact assessment step. The impact assessment step characterizes the flows in the LCI results in relation to a set of environmental impacts. For example, the impact assessment relates carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions (e.g., methane), to GWP (an impact). Finally, the interpretation step examines the results in accordance with the goals of the LCA study.

4.1 Environmental LCA Goal and Scope Definition

The goal of [PV][2] LCAs is to generate environmental impacts for owning and operating residential solar photovoltaic systems in the United States. These impacts are combined with economic analysis to help the homeowners make cost-effective, environmentally-preferred solar investment decisions. The goal and scope definitions include defining the system boundaries, cut-off criteria, the functional unit, and the data collection strategy.

4.1.1 System Boundaries

Defining the system boundaries involves identifying the unit processes to be included and the main life cycle stages that are included in each product LCA. A unit process is the "smallest element considered in the LCI analysis for which input and output data are quantified."[1] The manufacture of a product usually involves many unit processes (e.g., ethylene production for input to the manufacture of the styrene-butadiene bonding agent used in stucco cement in cladding). Each unit process involves many inventory flows, some of which themselves involve other, subsidiary unit processes. The main unit processes requiring data collection are, at minimum, within the main life cycle stages defined in the system boundaries. These are:

- Raw Materials Production: production of the materials in the building products. Transportation of materials to a manufacturing facility as well as production of packaging materials are included in this stage.
- Manufacturing: manufacturing operations to build the product.
- Transportation to installation: Transportation of the finished, packaged product to the site of installation is generally done by truck or rail, as most of the products are produced in the United States. Some products are produced outside North America, and this transportation (by ocean freighter) is accounted for in these situations.
- Installation, where data are available.
- Use: use phase emissions for solar photovoltaic system products is captured by the electricity production based on the impacts of grid-based electricity reduction.
- End of Life: fate of the product at end of its life.

4.1.2 Cut-off criteria

ISO 14044 requires a cut-off criterion to be defined for the selection of materials and processes to be included in the life cycle stages above. Several criteria are used in LCA practice to decide which inputs are to be studied, including mass, energy and

---

[1] Sec. 3.34 of International Organization for Standardization (ISO) (2006b).

environmental relevance. For the product LCAs, the mass criterion was always applied, and a cut-off goal of 95% has been defined. Mass was used since masses of materials are most specifically defined and quantifying mass throughout the systems – including what is not included - is most straightforward. Energy and environmental relevance are more difficult to use since there is less certainty with these parameters to be able to claim that the goal has been met. For example, if energy to produce certain inputs in a system has uncertain values, then the basis with which to calculate total energy and missing energy becomes uncertain. Detailed information on the inputs of a product's system are gathered, and every effort is made to include the production data for all parts and materials. The product chapters highlight where specific data are missing.

4.1.3 Exclusion from System Boundaries

Human activities are excluded from the system boundaries of the LCAs of these building products. Humans are involved in all aspects of the life of these products (factory workers driving to and from work, generating waste at the facility; transporters; users of the products…). These activities could be included in the system boundaries, but human activities are generally excluded from an LCA since it can be argued that these same people would still contribute to environmental factors whether or not they are contributing to the production or use of these products. Capital equipment is excluded except sometimes, when it is included as part of a background data set.

4.1.4 Functional Unit

To conduct an ISO-compliant LCA, all flows within the system boundaries must be normalized to a unit summarizing the function of the system, enabling the comparison of products or systems on an equivalent basis. The functional unit is thus defined so that the products compared may be true substitutes for one another. The functional unit provides the critical reference point to which all inventory flows are scaled. The functional unit for the LCA modeling of a solar photovoltaic system is the service life of the system. The functional unit for the LCA modeling of grid-based electricity is one unit of electricity consumed on-site as the building. In [PV]^2, the functional unit is the installation and operation (and replacement if necessary) of the solar photovoltaic system over the selected study period.

4.1.5 Data Requirements

Data requirements are defined in the scoping phase as well. ISO 14044 Section 4.2.3.6 highlights data quality requirements for an LCA, including:

- Representativeness – the qualitative assessment of degree to which the data set reflects the true population of interest. Representativeness includes geography (i.e., area covered), temporal data (i.e., the age of data and length of time over which data should be collected), and technological coverage (i.e., the technology mix);
- Consistency – the qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;

- Reproducibility – the qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study;
- Precision – the measure of the variability of the data values for each data category expressed;
- Completeness – the percentage of locations reporting primary data from the potential number in existence for each data category in a unit process.

These are described in in the Data Quality Evaluation section.

4.2 Inventory Analysis

Inventory analysis entails quantifying the inputs and outputs for the unit processes within a product system. One of the primary tasks is data collection that ensures the product system evaluated is representative and appropriately addresses the cut-off criteria, data and data quality requirements, and other scoping factors. Data are collected for each defined unit process. As shown in Figure 4-1, to produce a given product or intermediate product, inputs collected include energy, fuels, net water use, ancillary materials, and product components/materials. Outputs may include direct emissions to air and water, and waste categories.

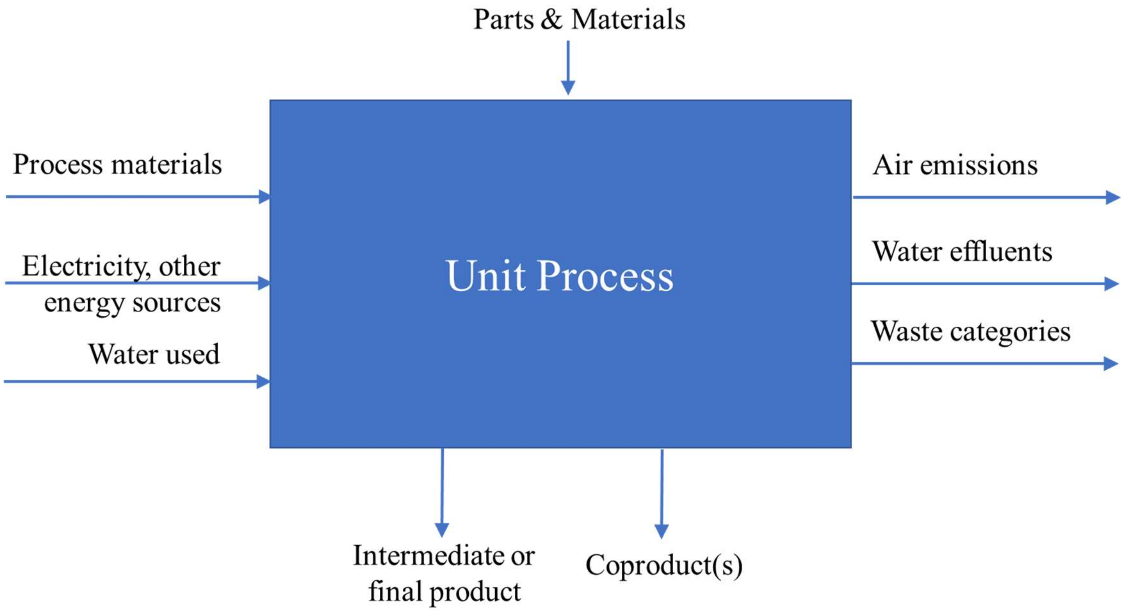


Figure 4-1 BEES Inventory Data Categories

Numerous approaches may be used to collect inventory data for LCAs. These range from (EPA, 1993):

- Unit process- and facility-specific: collect data from a process within a given facility that are not combined in any way
- Composite: collect data from the same process combined across locations

- Aggregated: collect data combining more than one process
- Industry-average: collect data derived from a representative sample of locations believed to statistically describe the typical process across technologies
- Descriptive: collect data whose representation may be unknown, but which are qualitatively descriptive of a process

For the solar photovoltaic system, U.S.-average data and results, generic product data are primarily collected using the industry-average approach. It is NIST's goal to strive for product data that represents the closest approximations available of the impacts and attributes associated with each product. Some of the products are built using detailed LCA questionnaires and/or shorter surveys sent to industry experts, while others are built using published LCA reports. In most cases, any assumptions regarding the associated unit processes are verified through experts in the respective industries to assure the data have been appropriately represented. Today, many industry average and company specific products have already-published EPDs, which are based on externally verified LCAs. For products in $[PV]^2$ that have undergone the EPD process, much, if not all, of the product data come from the EPDs' supporting LCAs, with the approval of the EPD owner.

Databases take care of background data sets, which are the supporting data for the products' defined unit processes. Background data can include materials, energy and fuel inputs, and transportation. Where manufacturers do not have control over data on their products, such as whether their product is recycled or landfilled at end of life, the LCA practitioner uses industry-backed data on the typical practice.

4.3 Life Cycle Impact Assessment

4.3.1 Methodology

Environmental impacts from building construction and use derive from the inputs and outputs occurring throughout production supply chains. The LCIA step of LCA quantifies the potential contribution of these inventory items to a range of environmental impacts. The approach preferred by most LCA practitioners and scientists today involves a two-step process:

- *Classification* of inventory flows that contribute to specific environmental impacts. For example, greenhouse gases such as carbon dioxide, methane, and nitrous oxide are classified as contributing to climate change.
- *Characterization* of the potential contribution of each classified inventory flow to the corresponding environmental impact. This results in a set of indices, one for each impact, which is obtained by weighting each classified inventory flow by its relative contribution to the impact. For instance, the Global Warming Potential (GWP) index is derived by expressing each greenhouse gas in terms of its equivalent amount of carbon dioxide heat trapping potential.

There are two general applications of this LCIA approach. The midpoint-level analysis quantifies environmental burdens along the cause-effect chain. There are many mid-point categories which make straightforward interpretation challenging, but mid-point calculations are generally more scientifically defensible. The endpoint-level analysis takes the mid-point calculations further and attempts to measure the ultimate damage that each environmental input and output in the inventory has along the cause-effect chain. Endpoint categories, such as damage to human health, ecosystems, and resource availability, make interpretation easier, but this approach is criticized for the numerous assumptions, value judgments, and gaps in coverage of the underlying damage models.

The midpoint-level analysis does not offer the same degree of relevance for all the impact categories. For global and regional effects (e.g., climate change and acidification) the method provides an accurate description of the potential impact. For impacts dependent upon local conditions (e.g., smog), it may result in an oversimplification of the actual impacts because the indices are not tailored to localities. Note that some impact assessments apply a mix of midpoint and endpoint approaches. It should be emphasized that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

PV^2 uses the midpoint-level analysis to translate its environmental inputs and outputs into a manageable set of science-based measurements across environmental impacts. The LCIA methodology uses U.S. Environmental Protection Agency's (EPA) Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) version 2.1 set of state-of-the-art, peer-reviewed U.S. life-cycle impact assessment methods (Bare, 2011). Additionally, Total Primary Energy Consumption is used to provide life-cycle primary energy associated with the building. Together these methods are used to develop performance metrics indicating the degree to which construction and use of a building contributes to each environmental impact. What follows are brief descriptions of the impact categories.

4.3.2 Global Warming Potential (CO_2e)

The Earth absorbs radiation from the Sun, mainly at the surface. This energy is then redistributed by the atmosphere and ocean and re-radiated to space at longer wavelengths. Greenhouse gases in the atmosphere, principally water vapor, but also carbon dioxide, methane, chlorofluorocarbons, and ozone, absorb some of the thermal radiation. The absorbed energy is re-radiated in all directions, downwards as well as upwards, such that the radiation that is eventually lost to space is from higher, colder levels in the atmosphere. The result is that the surface loses less heat to space than it would in the absence of the greenhouse gases and consequently stays warmer than it would be otherwise. This phenomenon, which acts like a 'blanket' around the Earth, is known as the greenhouse effect.

The greenhouse effect is a natural phenomenon. The environmental issue is the change in the greenhouse effect due to emissions (an increase in the effect) and absorptions (a decrease in the effect) attributable to humans. A general increase in temperature can alter atmospheric and oceanic temperatures, which can potentially lead to alteration of natural circulations and weather patterns. A rise in sea level is also predicted from an increase in temperature due to thermal expansion of the oceans and the melting of polar ice sheets.

4.3.3 Total Primary Energy Consumption and Related Energy Categories (MJ)

Total primary energy consumption comprises all energy associated with a product system, including energy used as fuel for product manufacturing as well as upstream and downstream processes (raw material production, transportation, operational use, etc.). Primary energy also includes the embodied energy of a product, such as hydrocarbons embodied in plastics. Total primary energy is broken down into **renewable** and **non-renewable energy** and **fossil fuel energy**. Non-renewable energy accounts for the energy coming from fossil fuels and other non-renewable resources used such as uranium for nuclear power. Hydropower, wind, geothermal, and biomass energy are classified as renewable. Fossil fuel energy quantifies the energy coming only from the fossil fuels including petroleum, natural gas, and coal. All these categories are reported in megajoules (MJ).

4.3.4 Acidification Potential (SO_2e)

Acidifying compounds may, in a gaseous state, either dissolve in water or fix on solid particles. These compounds reach ecosystems through dissolution in rain or wet deposition and can affect trees, soil, buildings, animals, and humans. The two compounds principally involved in acidification are sulfur and nitrogen compounds, with their principal human source being fossil fuel and biomass combustion. Other compounds released by human sources, such as hydrogen chloride and ammonia, also contribute to acidification.

4.3.5 Eutrophication Potential (Ne)

Eutrophication is the addition of mineral nutrients to the soil or water. In both media, the addition of large quantities of mineral nutrients, such as nitrogen and phosphorous, results in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water, it tends to increase algae growth, which can lead to a lack of oxygen and subsequent death of species like fish.

4.3.6 Smog Formation (O_3)

Smog forms under certain climatic conditions when air emissions (e.g., nitrous oxides (NO_X), volatile organic compounds (VOCs)) from industry and transportation are trapped at ground level where they react with sunlight. Smog leads to harmful impacts on human health and vegetation.

4.3.7 Ozone Depletion (CFC-11e)

Ozone depletion is the thinning of the stratospheric ozone layer, allows more harmful shortwave radiation to reach the Earth’s surface, potentially causing undesirable changes in ecosystems, agricultural productivity, skin cancer rates, and eye cataracts, among other issues.

4.3.8 Respiratory Effects (PM2.5e)

Respiratory effects look at particulate matter and air emissions generated by use of fuels for manufacturing and transportation and materials handling, that when inhaled, may result in health issues such as asthma and other respiratory illnesses. This impact category is reported in kg PM2.5-eq (particulate matter of size less than or equal to 2.5 micrometers).

4.4 Solar Photovoltaics

Photovoltaics is the term used to describe the method of generating direct current electricity from solar energy. Generally, photovoltaic panels, or solar panels, are composed of solar cells that supply usable solar power. The solar inverter converts the direct current (DC) electricity produced by solar cells into an alternating current (AC) that can be utilized directly or transferred back to the electrical grid.

Previously developed for BIRDS NEST, models were developed that specify four different solar panels and their racking hardware; three different inverter systems; and an electronic monitoring device. Each system is modeled based on a functional unit of one watt (W). The individual components have been calculated on a per-kilowatt-potential (kWp) basis, as this can be translated to any sized system and is not dependent on location.

The homeowner is unlikely to know where the manufacturing facility of the solar panels is located. Therefore, the model for $[PV]^2$ currently hard-codes the source country for the solar panels to U.S.-based production. An option could be included in a future version to provide greater granularity. This could be accomplished by adding a database of solar panel brand and product lines that includes their manufacturing facility locations.

Figure 4-2 presents the photovoltaic system boundaries.

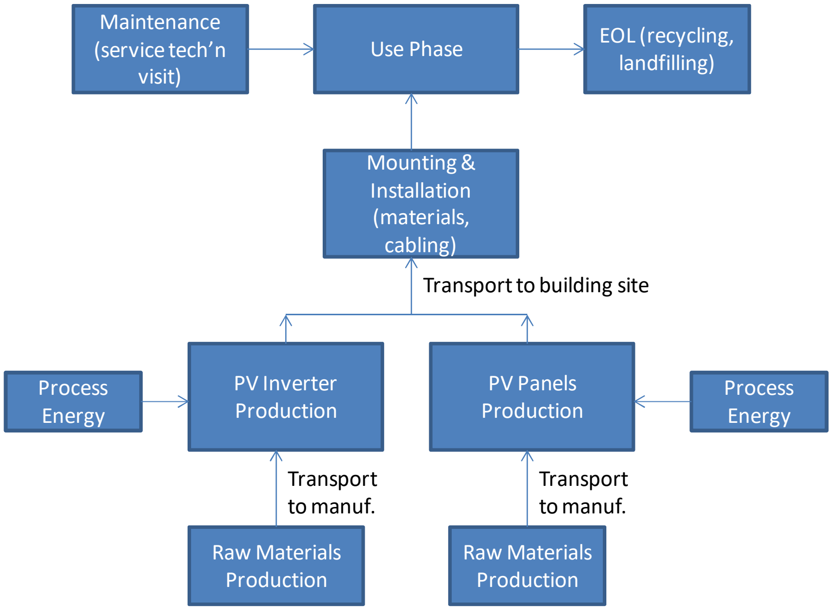


Figure 4-2 Solar Photovolatic System Boundaries

4.4.1 Upstream Materials Production through Manufacturing

Manufacturer-specific data were not available, so publicly available sources of data were used. Specifically, the crystalline silicon solar panel, inverter, and associated cabling are based on research by Mariska De Wild and Erik Alsema (Fthenakis, 2011), which were compiled by ecoinvent to build comprehensive inventories. (Jungbluth, 2007)

4.4.2 Photovoltaic Panels and Racking System

Photovoltaic panels. The photovoltaic panels include:

- monocrystalline panel with premium efficiency (i.e., greater than 20 %),
- monocrystalline panel with average- to above-average efficiency (i.e., 15 % – 20 %),
- polycrystalline panel with average efficiency (i.e., 13 % – 16 %) that are mass-produced in the U.S., and
- polycrystalline panel with average efficiency (i.e., 13 % – 16 %) that are mass-produced in in China.

The silicon solar panel LCI data in ecoinvent were provided by industry yet are not manufacturer specific. They can be considered a reliable representation of crystalline silicon module production technology for 2005/2006 and are based on Western Europe production. Due to the detailed bill of materials, the data are not presented in this report. However, Figure 4-3 is provided to provide clarity around the processes involved in the production of these solar panel using a monocrystalline solar panel as an example (Fthenakis, 2011).

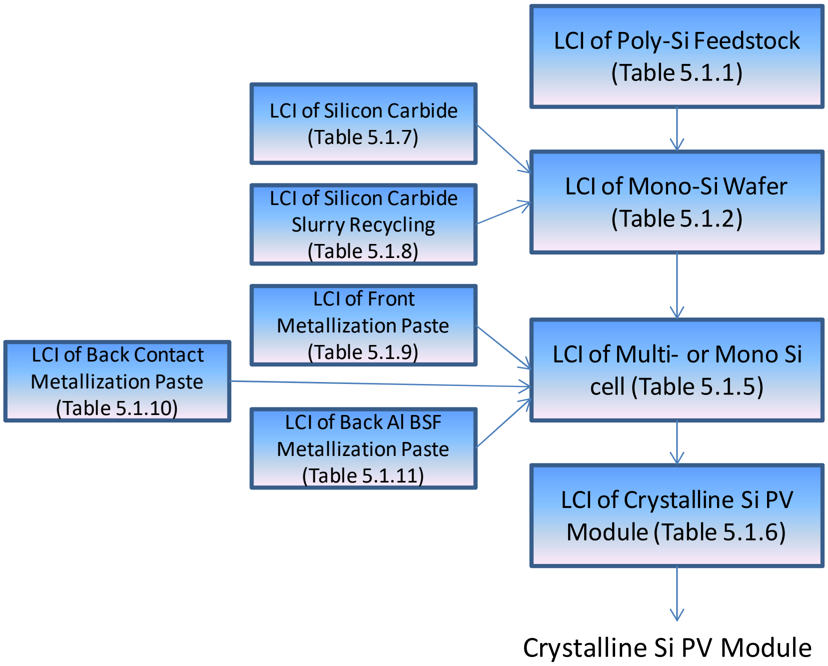


Figure 4-3 PV Module Production Data Sets

To build solar panel models that are representative of products on the market today, a web search was performed to understand specifications for more current products on the market. Then the ecoinvent datasets that were most closely aligned with the products on the market were adjusted to the current products' general specifications, as shown in Table 4-1. The last item in the table represents the racking or mounting hardware.

Table 4-1 PV Panels Specifications & Data Sets

	Panel area, m^2 (ft^2)	Watt potential per panel (Wp)	Weight, kg (lb)	Area/Wp, m^2 (ft^2)	Wt/Wp, kg (lb)
Monocrystalline Panel (>20%) note 1	1.63 (0.15)	280	18 (39.7)	0.0058 (5.6 E-4)	0.064 (0.14)
ecoinvent data set and value used →	Photovoltaic panel, single-Si wafer production ~ 0.006 m^2 (5.6 E-4 ft2)				
Monocrystalline Panel (15-20%) note 2	1.86 (0.18)	415	21.1 (46.5)	0.0045 (4.7 E-4)	0.051 (0.11)
ecoinvent data set and value used →	Photovoltaic panel, single-Si wafer production ~ 0.005 m^2 (4.7 E-4 ft2)				
Polycrystalline Panel (13-16%), China note 3	1.63 (0.15)	250	19.5 (43.0)	0.0065 (6.6 E-4)	0.078 (0.17)
ecoinvent data set and value used →	Photovoltaic panel, multi-Si wafer production, using avg China electricity grid ~ 0.007 m^2 (6.6 E-4 ft^2)				
Polycrystalline Panel (13-16%), U.S. note 3	1.63 (0.15)	250	19.5 (43.0)	0.0065 (6.6 E-4)	0.078 (0.17)
ecoinvent data set and value used →	Photovoltaic panel, multi-Si wafer production, using avg U.S. electricity grid ~ 0.007 m^2 (6.6 E-4 ft^2)				
Racking / Mounting system	Photovoltaic mounting system, for slanted-roof installation (RoW)| production				

Note 1: Product data based on Solar PV Module HON-M60B, found at: https://cdn.enfsolar.com/Product/pdf/Crystalline/5b724fc42aece.pdf?_ga=2.251271110.1151162136.1565887874-1576003210.1565887869.

Note 2: Product data based on SunPower 400–425 W Residential AC Module, found at: https://es-media-prod.s3.amazonaws.com/media/components/panels/spec-sheets/SunPower_A-Series.pdf

Note 3: Product data based on TrinaSolar TSM-PC/PA05A, found at: https://www.energymatters.com.au/images/trina-solar/trina-pc05a-250w.pdf

Since the data are based on Western Europe, wherever possible, data representing North American production were used to adjust the data to be more appropriate for North American conditions; U.S. LCI database and other North American data sets were used to replace some of the process energy, transportation, and upstream materials data sets (e.g., framing materials, auxiliary materials, etc.). For the polycrystalline panel produced in China, the China electricity grid was applied. Detailed information is provided in the tables referenced in Figure 4-3 and/or Jungbluth (2007).

Racking system. For the racking system, the industry weighted-average materials and processes in Fthenakis (2011) Table 5.4.2 were used. The data are provided for 1 m^2 (10.8 ft^2) of a mounted PV module on a slanted roof. This was normalized to the Wp values corresponding with the panel areas listed in Table 4-1. Data for electrical cabling for module interconnection and AC-interface is provided by Fthenakis (2011) Table 5.5.1.1, and is provide in Table 4-2.

Table 4-2 Solar Panel Mounting Materials and Cabling

Mounting Material	**kg per m^2**	**lb per ft^2**	**Notes**
Aluminum	2.84	0.58	plus section bar rolling
Corrugated board	0.013	0.003	
Polyethylene	0.0013	0.0003	
Polystyrene	0.006	0.0013	
Low-alloyed steel	1.50	0.31	plus steel sheet rolling
Cabling Material			
Copper	0.10	0.021	2.2 m DC cable and 0.1 m AC cable
Thermoplastic elastomer	0.06	0.013	

4.4.3 Photovoltaic Inverters and Electronic Monitoring System

Photovoltaic Inverters. The inverters used in [PV]^2 include a string inverter, a microinverter, and a string inverter with an optimizer. The string inverter is one of the most common types of inverters used in residential applications. A string inverter is connected to a "string" of solar panels, converting power from DC to AC for all the panels. Microinverters are smaller-sized and attach to each panel instead of one central inverter. While micro-inverters are more expensive to install, they are useful when part of a panel is in the shade or if the roof is too small to have a string of panels. When an optimizer is installed with an inverter, the optimizer improves overall system performance and can draw from individual panels to maintain output (i.e., when part of the system is shaded).

Inverters in ecoinvent, described in (Jungbluth, 2007), were normalized to a Wp output based on their rated capacity in the data sets. Table 4-3 presents the data sets and the quantity of each unit applied per Wp.

Table 4-3 PV Inverters Data Sets Used

	ecoinvent Data Set & Quantity per Wp	**Notes**
String Inverter.	Inverter, 2.5kW (RoW)| production ~ 0.0004 unit	
Inverter & Optimizer	Inverter, 2.5kW (RoW)| production ~ 0.0004 unit	
	Optimizer: used Electronics, for control units (RoW)| production	Proxy for 1.2 kg (2.7 lb) optimizer
Micro Inverter	Inverter, 0.5kW (Dorer & Weber)| production ~ 0.002 unit	

Materials are modeled as transported to the manufacturing plant via diesel truck an assumed average distance of 805 km (500 mi). Transportation data come from the U.S. LCI database.

Solar Monitoring System. Solar power monitoring systems enable homeowners to monitor solar electricity production and/or the home's energy usage. Monitors are often small electronic devices; the data set used as a proxy for a monitor on the market is the ecoinvent LCD module. Monitors are small and efficient; the monitor in [PV]^2 is modeled after a 9.0 g (0.02 lb) device and is assumed to work for a 3000 Wp system.[2]

4.4.4 Transportation to the Building Site through End of Life

Transportation of the solar panels and other components in this system an assumed average of 2414 km (1500 mi) by heavy-duty diesel fuel-powered truck. The exception to this is the transport from China, in which ocean freighter from Asia to the U.S. West Coast is added to the model.

It is assumed that a qualified service technician comes to the building site once annually to check the PV system to ensure optimal performance and lifetime. It is assumed that the technician is within a 24 km (15 mi) service radius. This distance, driven in a gasoline-powered van, is shared amongst other service visits for that technician. Assuming the technician makes 5 service calls in one day, one-fifth of the impacts from driving 24 km (15 mi) are allocated to the product, or 4.8 km (3 mi). Data for a van come from ecoinvent. Unplanned service visits (i.e., unanticipated issues that require a service technician) are not included in the model under the assumption that the system will run as designed given the homeowner sufficiently follows the maintenance and care guidelines.

Over time, PV panels can degrade at a rate of one percent per year. The Solar Energy Industries Association (SEIA) states that the lifespan of solar panels can last from 20 to 30 years (SEIA, 2015). [PV]^2 models the monocrystalline panels with a 30-year lifetime while the polycrystalline are assumed to have a 20-year lifetime. SEIA (2015) states a lifetime of 10 years for the inverter. The racking system has a lifetime of 60 years or beyond. The monitoring system is re-purchased after 10 years.

At end of life, materials from solar panels are assumed to be sent for recycling for material recovery. The recycling process for silicon-based modules can be described as follows: "For silicon-based modules, aluminum frames and junction boxes are dismantled manually…. The module is subsequently crushed and its several components are separated, allowing recovering up to 80% of the panel."[3] An LCA screening study by Fraunhofer (2012) demonstrated that valuable materials like aluminum frames, copper, and glass cullet can be successfully recovered at a flat glass recycling facility. At the time of this writing, in the U.S., recycling of PV panels is not mandated. However, it is expected that as recycling of PV panels becomes a streamlined operation and as PV panels begin to exceed their useful lives, recycling will be industry standard practice. Note that PV panels are required to be recycled in the EU today.[4]

---

[2] See, for example, the geo Solo II Home Energy Monitor, found at: https://www.amazon.co.uk/geo-Solo-Home-Energy-Monitor/dp/B00NFSO122.

[3] See: http://www.solarwaste.eu/collection-and-recycling/.

[4] In 2012, solar panels fell under the scope of the Directive on waste electrical and electronic equipment (WEEE), which means that producers of solar panels are required to fund collection, treatment, and recycling of WEEE and divert it from landfills.

A distance of 48 km (30 mi) to the landfill or a recycler in a heavy-duty diesel truck has been modeled. The landfill is based on ecoinvent waste management process data.

4.5 Operational Electricity

Operational electricity production inventory data are applied to a building's consumption and production of electricity to convert site flows to source flows, which are customized to a specific location based on the user provided location (specifically ZIP code) to calculate the operational electricity LCA results.

4.5.1 Temporal Scope

The "BENCHMARK" option is an attributional LCA using the current state of the electricity commodities/technologies to develop a consumption-based snapshot in time using the average fuel mix of a unit of consumption in a given location for the year the data was collected (currently 2018). This option assumes the same operational electricity LCA data for all years of the analysis study period. The benefit of using a consumption-based LCA is that it accounts for the fact that the unit of energy consumed at a building site does not necessarily match the generation occurring within the market region in which the building is located due to electricity trading across market regions.

DOE's National Energy Technology Laboratory (NETL) developed a reproduceable model for generating these attributional LCA and LCIA results using data profiles for electricity production consumed in the United States. The life cycle data profiles are documented in a forthcoming NETL-published report and will be available for download in an associated spreadsheet. The primary data source details for each fuel type are listed in Table 4-4.

Table 4-4 Operational Energy LCA Data Sources

Fuel Type	Regionalization	Data Source	Developer	Data Year
Electricity	Balancing Authority	U.S. Electricity Baseline Model	Federal LCA Common / NETL Grid Mix Explorer	2018

The other two options use the attributional model results and EIA Annual Energy Outlook 2021 (AEO2021) projections to develop generation based LCAs to allow for changing the projected fuel mixes over time. Electricity will realize significant changes in the environmental impacts associated with its generation and consumption because the fuel mix has been changing and will continue to change over the next few decades. The "Projection – Baseline" option uses the AEO2021 Reference case as the basis for the assumed change in electricity fuel mix out to 2050 while the "Projection – High Renewable" option uses the AEO2021 Low Renewable Cost case.

Figure 4-4 is the figure on page 1 of EIA (2021), and shows that the AEO2021 Reference case projects electricity generation from renewables will double its share of total generation from 21 % in 2020 to 42 % in 2050. The Low Renewable Cost case would lead to an even higher renewable share of 57 % by 2050. These significant changes in the fuel mix will lead to changes in the environmental impacts of a unit of electricity consumption. For example, EIA projects that from 2020 to 2050, the total annual carbon emissions from the electric power sector will be reduced by 14 % while total electricity sales will increase by 30 % over the same timeframe.

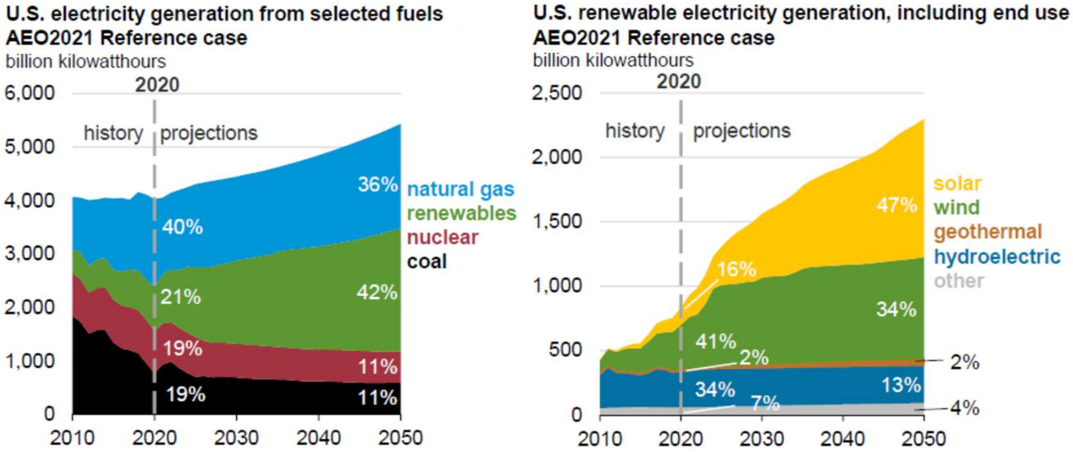


Figure 4-4 Electricity Generation by Fuel – AEO2021 Reference Case

These national average projections express the significant changes that are expected to occur in the U.S. electric grid over the next 30 years under current regulatory and economic conditions. The fuel mix projections across balancing authorities vary significantly both in terms of the initial state of the fuel mix and the expected change in the fuel mix over time. By controlling for these differences, BIRDS NEST can provide more accurate LCA data projections for electricity for a given building location.

There are two limitations that should be acknowledged for the current electricity LCA development process. First, the electricity generation fuel mix in a balancing authority can change significantly from season to season, day to day, and even hour to hour. It would be technically feasible to identify the marginal generating unit for each hour of every day and develop an LCA for each of these units. However, a homeowner will not have access to the necessary data. A solar installer will provide estimated annual production (typically only for the initial year of operation) of the solar photovoltaic system, making it impossible to identify the marginal generating unit for sub-annual time periods. Second, the incorporation of battery storage related LCA data is not currently included in future projection cases. The implications of battery storage are difficult to model because of the fast-moving technological advances and the quickly shifting economics of battery storage. Future updates to the operational electricity data could consider including sub-annual variation in fuel mixes as well as incorporate battery storage projections if it is determined to be beneficial.

4.5.2 Geographic Scope

The geographical scope of the operational electricity LCA data are at the U.S ZIP code level for the continental United States. Each ZIP code is mapped to appropriately defined EIA market regions (i.e., Balancing Authority). Note that the mapping of ZIP code to these regions requires subjective assignment in geographical areas where the ZIP code applies to more than one market region. The nearest neighbor approach aligned to the geographical resolution of the underlying data for each energy commodity is used in these situations.

The 66 U.S. balancing authorities are used as the market regions for electricity. Figure 4-5 shows the North American Electric Reliability Corporation (NERC) regions and the balancing authorities within those NERC regions developed by the EIA (EIA, 2016). Detailed information is available at the balancing authority level on electricity generation, consumption, and inter-balancing authority trading, providing a more accurate estimate of the average fuel mix for a given location than the commonly used NERC region level data. It is not realistic to use further disaggregated data because a unit of electricity cannot be tracked through the balancing authority grid. As can be seen in Figure 4-5, balancing authorities do not always align with state and/or county borders, making it inappropriate to map to those boundaries. Although the same issues may arise to a lesser extent with the use of ZIP codes, the level of precision is much higher and the potential geographical area that could be mismatched is minimized.

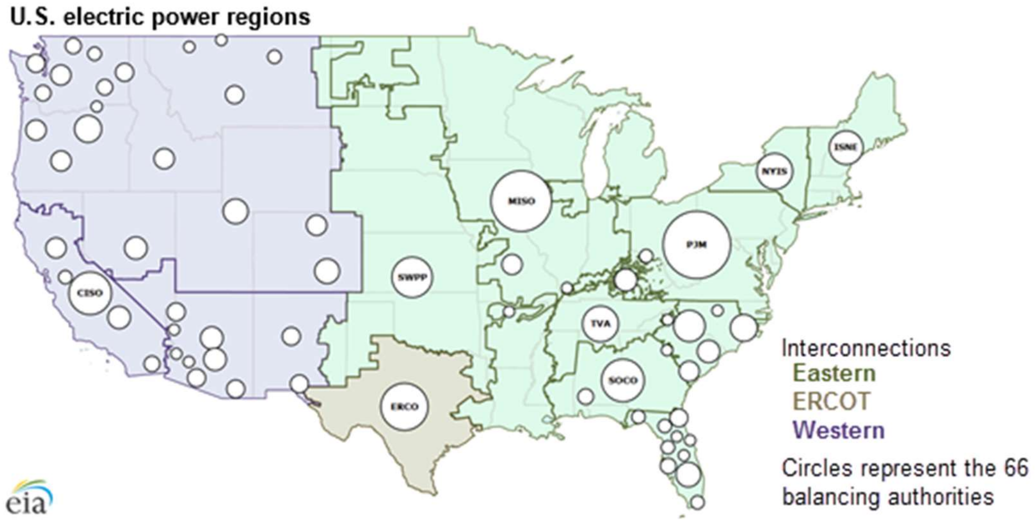


Figure 4-5 NERC Regions and Balancing Authorities

4.5.3 LCA and LCIA Methodology

The LCA development is cradle-to-grave for on-site electricity consumption. All known air and water emissions contributing greater than 1 % to each impact assessment methodology. The scope of emissions data is limited to emission data that industry reports to the U.S. government; specifically, the EIA and EPA. Note that discussions have begun to expand the U.S. Electricity Baseline to include Canada and Mexico to provide a North American Electricity Baseline to improve consistency of background operational energy LCA data. The operational energy LCA data will be updated annually and incorporate the most up-to-date data available as well as any improvements and/or expansions of the Electricity Baseline model.

The LCIA methodology is consistent with the solar photovoltaic system LCA. The data includes all the impact categories as described in Section 4.3 as well as three other TRACI 2.1 impact categories (Carcinogenic Potential, Non-carcinogenic Potential, Ecotoxicity Potential). These additional impact categories are excluded from any further discussion in this document because they are not included in PV^2.

GWP Potential is provided using both the TRACI 2.1 life cycle impact assessment methodology and International Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) GWP values with climate feedback. The option was designed into the process to allow users to select which option best fits their LCA modeling requirements and/or preferences. PV^2 uses the TRACI 2.1 methodology and will remain consistent with that methodology moving forward. Any updates to TRACI 2.1 will be incorporated into the underlying data sources. As with the solar photovoltaic system LCA data, Total Primary Energy Consumption is based on the ecoinvent methodology as described in Frischknecht (2007) that uses Cumulative Energy Demand (CED).

Total operating electricity-related LCIA ($TLCIA_{E,i}$) for each environmental impact category (i) over study period "T" for a building are estimated using the following formula where EC_t is electricity consumption in year t, EP_t is electricity production in year t, and $LCIA_{E,i,t}$ is the electricity LCIA for impact category i in year t:

$$TLCIA_{E,i} = \sum_{1}^{T} \left((EC_t - EP_t) * LCIA_{E,i,t} \right)$$

$LCIA_{E,i,t}$ is constant over time for the Benchmark option and variable for the two projected options. On-site electricity production from solar photovoltaics is assumed to offset the equivalent consumption-related emissions. The solar photovoltaic production is assumed to degrade at an annual rate of 0.5 % ($EP_{t-1} = EP_t * (1 - 0.005)$) while electricity and natural gas consumption is assumed constant ($EC_1 = EC_2 = \cdots = EC_T$ and $GC_1 = GC_2 = \cdots = GC_T$).

5 Software Development and Design

[PV]^2 is a web application that enables a user to evaluate the economic (through life cycle cost analysis) and environmental (through life cycle assessment) performance installing a rooftop solar photovoltaic system on a house using quotes from a solar installer and electric bill information as described in previous sections of this report. Comparisons of life cycle costs and environmental impacts for installing a solar photovoltaic system versus continued purchase of grid-based electricity from the electricity provider can be evaluated using the data visualization features in the application. Technologies were selected for this project based on their utility in developing this comprehensive system. A summary of each technology is described below.

5.1 [PV]^2 Application

Several web technologies were used in the creation of the [PV]^2 user interface. Hypertext Markup Language (HTML) is the primary language used for displaying web content. Cascading Style Sheet (CSS) is the definition file used by web pages for formatting. JavaScript is a light-weight scripting language used to programmatically manipulate the input, output or display of a web page. TypeScript is an open-source language that builds on JavaScript by providing a way to describe the shape of an object, providing better documentation, and allowing TypeScript to validate that the code is working correctly. Writing types can be optional in TypeScript, because type inference allows you to get a lot of power without writing additional code. Other development tools may be considered in the future if new capabilities and features require them, such as adding more significant background data sources for auto-populating parameter values (e.g., electricity prices, solar installation costs, solar panel specifications).

[PV]^2 takes the user inputs and creates a JavaScript Object Notation (JSON) file using the E3 input file format, sends the file to the E3 Application Programming Interface (API), waits and receives the E3 output file, and parses the results for display. By leveraging E3, the [PV]^2 web application does not require a back-end calculation engine, simplifying and accelerating its testing and development, including future expansion of its capabilities and features.

The software is extensively beta tested and validated internally using multiple examples before being released to ensure correct tool functionality, E3 input file creation, E3 output file creation, and parsing of results.

5.2 Economic Evaluation Engine (E3) API

5.2.1 Overview

The Economic Evaluation Engine (E3) is a free, publicly accessible API hosted on a NIST-maintained Amazon Web Services (AWS) instance as well as on GitHub for anyone to use for standards-based economic analysis, whether it's through a basic script calling on E3, online interface that connects to E3, or an executable program that is built on E3 capabilities. Additionally, users of E3 could provide validation of the current code and expansions to the capabilities by developing the code and submitting it to NIST for review and incorporation.

Previous software development by AEO/EL Data, Software, and Technology (ELDST) have been "one-off" tools that use similar (if not identical) back-end calculations. E3 has been designed as a generic API that can complete standards-based economic analysis regardless of topic area (e.g., buildings and infrastructure, community resilience, sustainable manufacturing) or analysis type (e.g., LCCA, benefit-cost analysis (BCA), profit maximization), which will allow AEO/ELDST to focus its collective resources on maintaining and expanding the API functionality and capabilities to keep it up-to-date and relevant instead of duplicating maintenance efforts across a range of software tools. Tools that leverage the API could be developed by AEO/ELDST (including transition of existing tools), other EL or NIST researchers, federal and state government agencies, academics, or the private sector (industry groups and individual companies) based on their analysis needs at lower costs because much of the back-end development would already be completed.

E3 has been developed with widely accepted and used open source tools throughout the development process, each of which is briefly discussed below. For additional details on E3, please see the E3 User Guide (forthcoming) and the E3 GitHub page (https://github.com/usnistgov/e3).

5.2.2 Programming – Python, numPy, and pytest

Python is an open source object-oriented, interpreted, and interactive programming language. Python combines power with clear syntax, and has modules, classes, exceptions, high-level dynamic data types, and dynamic typing. There are interfaces to many system calls and libraries, as well as to various windowing systems. New built-in modules are easily written in C or C++ (or other languages, depending on the chosen implementation). Python is also usable as an extension language for applications written in other languages that need easy-to-use scripting or automation interfaces. Python can be used for web, graphical user interface (GUI), and software development, system administration, and scientific and numeric analysis. NumPy is the fundamental package for scientific computing in Python. It is a Python library that provides a multidimensional array object, various derived objects (such as masked arrays and matrices), and an assortment of routines for fast operations on arrays, including mathematical, logical, shape manipulation, sorting, selecting, I/O, discrete Fourier transforms, basic linear algebra, basic statistical operations, random simulation and much more. Pytest is a mature full-featured Python testing tool. With pytest, common tasks require less code and advanced tasks can be achieved through a variety of time-saving commands and plugins. It will even run your existing tests out of the box including those written with Python's unittest module.

5.2.3 Framework – Django, Django REST Framework, and Django.test

Django is an open source, high-level Python web framework that encourages rapid development and clean, pragmatic design. Built by experienced developers, it takes care of much of the hassle of web development, allowing for focusing on writing the app without needing to reinvent the wheel. Django includes dozens of extras you can use to handle common web development tasks. Django takes care of user authentication, content administration, site maps, RDF Site Summary or Really Simple Syndication (RSS) feeds, and many more tasks. Django helps developers avoid many common security mistakes, such as Structured Query Language (SQL) injection, cross-site scripting, cross-site request forgery and clickjacking. Its user authentication system provides a secure way to manage user accounts and passwords. Django's quick and flexible scale can meet heavy traffic demands. Django can be used build content management systems to social networks to scientific computing platforms.

Django REST (representational state transfer) framework is a powerful and flexible toolkit for building Web APIs. REST framework has several benefits, including the web browsable API, authentication policies including packages for OAuth1a and OAuth2, serialization that supports both object-relational mapping (ORM) and non-ORM data sources, completely customizable, and extensive documentation, and excellent community support.

The Django test client (django.test) is a Python class that acts as a dummy web browser, allowing testing of views and interact with Django-powered applications programmatically. Some of the things test client can be used for include:

- Simulate GET and POST requests on a URL and observe the response.
- See the chain of redirects (if any) and check the URL and status code at each step.
- Test that a given request is rendered by a given Django template, with a template context that contains certain values.
- Use Django's test client to establish that the correct template is being rendered and that the template is passed the correct context data.
- Use in-browser frameworks like Selenium to test rendered HTML and the behavior of Web pages, namely JavaScript functionality.

5.2.4 Deployment – PostgresSQL, Docker, AWS

PostgreSQL is a powerful, open source, highly extensible object-relational database system with a strong reputation for reliability, data integrity, robust feature set, extensibility, and the dedication of the open source community behind the software to consistently deliver performant and innovative solutions. PostgreSQL runs on all major operating systems, has been ACID-compliant since 2001, and has powerful add-ons such as the popular PostGIS geospatial database extender.

Docker is an open platform for developing, shipping, and running applications. Docker enables you to separate your applications from your infrastructure so you can deliver software quickly. With Docker, you can manage your infrastructure in the same ways you manage your applications. By taking advantage of Docker's methodologies for shipping, testing, and deploying code quickly, you can significantly reduce the delay between writing code and running it in production. Docker provides the ability to package and run an application in a loosely isolated environment called a container. The isolation and security allow you to run many containers simultaneously on a given host. Containers are lightweight and contain everything needed to run the application, so you do not need to rely on what is currently installed on the host. You can easily share containers while you work, and be sure that everyone you share with gets the same container that works in the same way.

AWS offers information technology infrastructure services to businesses in the form of web services (i.e., cloud computing). The E3 Docker Container is hosted on am AWS instance.

6 Limitations and Future Development

The $[PV]^2$ web application has several limitations related economic assumptions, LCA modeling, and LCIA methodology. Each will be summarized below. Additionally, potential future development of new capabilities and features in the application are discussed.

6.1 Economic Assumptions

Numerous assumptions required to complete the economic analysis are uncertain. Estimating future costs accurately, particularly for costs more than a few years into the future, is difficult to impossible. Similarly, externality costs are difficult to estimate. The social cost of carbon varies depending on the underlying assumptions (e.g., discount rate). Additionally, electricity production each year, how long a household will own a home, and the service life of equipment can be estimated but are truly unknown. All a user can do is use the best information available at the time to make an optimal decision. It is recommended that the user consider completing a sensitivity analysis of any assumptions that they are concerned may change their decision.

6.2 LCA and Uncertainty

It should be borne in mind that LCA, like any other scientific or quantitative study, has limitations and is a far from perfect tool for assessing exact environmental impacts and attributes associated with products and product systems. Uncertainty exists throughout all levels of LCA, from the background data to impact characterization to normalization factors. Quantifying data uncertainty for the complete system becomes very challenging. Currently, $[PV]^2$ does not include a formal uncertainty analysis but NIST is evaluating the inclusion of uncertainty analysis into future releases.

Despite these limitations, it should be emphasized that, the LCAs are built based on the best data that were available at the time of the study using the same LCI database, utilizing the same background data sets (for example, for transportation data, energy production, and materials production), and care is taken – using internal checks and balances, external peer review, and product-specific modeling rules – to ensure that products in the same category are built appropriately and objectively.

6.3 LCIA

To assess environmental performance, LCA models' inventory flows are converted to various local, regional, and global environmental impacts. While $[PV]^2$ incorporates state-of-the-art LCIA methods, the science will continue to evolve, and methods in use today will continue to change and improve over time. Future versions will always incorporate improved methods as they become available and more universally accepted.

The Environmental Problems approach that $[PV]^2$ uses for impact assessment does not offer the same degree of relevance for all environmental impacts. For global and regional effects (e.g., climate change and acidification) the method may result in an applicable description of the potential impact. For impacts dependent upon local conditions (e.g., smog and particulate matter) the method may result in an oversimplification of the actual impacts because the indices are not tailored to localities.

6.4 Additional Features and Capabilities

There is potential to expand the capabilities and features in $[PV]^2$, including the addition of more default data, methodology, system equipment, and results comparison options, combination with other solar-related software, and sensitivity and uncertainty analysis.

Default data options could be expanded for electricity prices by location, installed costs by location and technology, and solar panel specifications. Underlying databases would need to be developed and maintained to complete these matches, and reliable and up-to-date data sources would need to be identified. Examples of potential data sources could include the following:

- Electricity price data
    - OpenEI Utility Rate Database - https://openei.org/wiki/Utility_Rate_Database
- Solar photovoltaic installed costs data
    - EnergySage - https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/
    - Tracking the Sun –https://emp.lbl.gov/tracking-the-sun
- Solar panel specifications data
    - EnergySage - https://www.energysage.com/solar-panels/?product_line_status=current
    - NREL – System Advisor Model (SAM) - https://sam.nrel.gov/

Methodology options could be expanded, such as the residual value approaches. Instead of only allowing the linear depreciation approach, one or more alternative approaches could be included. Specifically, the remaining production value and/or the expected increase in resale value of the home could be included.

System equipment options could be expanded to include battery storage options, which are becoming more common as the cost of batteries has dropped significantly in the last 5 years. The costs of battery storage would be straight forward to include in $[PV]^2$. However, the economic benefits to a homeowner would require including low-probability, high-impact events related to increased resilience (i.e., avoiding power outages).

The current version of $[PV]^2$ allows the user to analyze a specific quoted solar photovoltaic system. However, each solar installer may provide different equipment options that have different designs, prices, and performance. Additionally, most solar installers will provide multiple system and size options depending on the homeowner's stated goals (e.g., value versus quality, optimal production versus offsetting current consumption) and constraints (e.g., budget, roof structure). A user could run analysis for each system and then manually compare the results using either the Portable Document

Format (PDF) reports or the results data in the CSV files. However, allowing such a comparison from within the tool would be beneficial to help a homeowner quickly narrow their investment options.

Communication with other software tools to leverage their capabilities could be beneficial for users that are trying to determine if a solar photovoltaic system is a viable option and worth reaching out to get solar installation quotes. A user could use other tools that are currently available, such as EnergySage's Solar Calculator (https://www.energysage.com/solar/calculator), NREL's PVWatts (https://pvwatts.nrel.gov/), or PVValue (https://www.pvvalue.com/). Some of the features in these tools would be beneficial to incorporate into $[PV]^2$, either directly or through interoperability with those tools. Another tool that is not necessarily useful for homeowners, but could provide some excellent capabilities through interoperability is NREL's SAM model (https://sam.nrel.gov/).

E3 has the capabilities to provide both sensitivity analysis and uncertainty analysis. $[PV]^2$ could introduce sensitivity analysis, initially with the most important parameter values in the economic analysis that are uncertain (e.g., solar panel service life, energy price escalation rates) and allow user feedback to determine if more robust sensitivity analysis or uncertainty analysis (e.g., Monte Carlo analysis) should be introduced as well.

References

Alberini, A., & Chiabai, A. (2007). Discount Rates in Risk Versus Money and Money Versus Money Tradeoffs. *Risk Analysis, 27*(2), 483-498. doi:https://doi.org/10.1111/j.1539-6924.2007.00899.x

ASTM. (2015). *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems, ASTM Designation E917-15*. Retrieved from West Conshohocken, PA:

ASTM. (2017). *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems, ASTM Designation E917 – 17*. Retrieved from West Conshohocken, PA:

Barbose, G., Darghouth, N., O'Shaughnessy, E., & Forrester, S. (2020). *Tracking the Sun - Distributed Solar 2020 Data Update - Summary Data Tables*.

Bare, J. (2011). TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy, 13*(5), 687-696.

Cameron, T., & Gerdes, G. (2002). *Eliciting Individual-Specific Discount Rates*. Paper presented at the Second World Congress of Environmental and Resource Economists, Monterey, CA.

Dorer, V., & Weber, A. (2009). Energy and CO2 emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs. *Energy Conversion and Management, 50*(3), 648-657.

EIA. (2016). U.S. electric system is made up of interconnections and balancing authorities. *Today in Energy.*

EIA. (2021). *Annual Energy Outlook 2021 - Electricity*. https://www.eia.gov/outlooks/aeo/pdf/04%20AEO2021%20Electricity.pdf

EPA. (1993). *Life Cycle Assessment: Inventory Guidelines and Principles*. Retrieved from

Fraunhofer. (2012). *Executive Summary: Life Cycle Assessment (LCA) screening of the Maltha recycling process for Si-PV modules*. Retrieved from http://www.pvcycle.org/:

Frischknecht, R. J., N.; Althaus, H.J.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Margni, M.; Nemecek, T.; Spielmann, M. (2007). *Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3*. Retrieved from Dübendorf, Switzerland:

Fthenakis, H. C. K., R. Frischknecht, M. Raugei, P. Sinha, M. Stucki. (2011). *Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems*. Retrieved from

International Organization for Standardization (ISO). (2006a). Environmental Management -- Life-Cycle Assessment -- Principles and Framework, International Standard 14040. In.

International Organization for Standardization (ISO). (2006b). Environmental Management -- Life-Cycle Assessment -- Principles and Framework, International Standard 14044. In.

Jungbluth, N. a. T., M. (2007). *Photovoltaics*. Retrieved from

Kneifel, J., & Webb, D. (2020). *LIFE CYCLE COSTING MANUAL for the Federal Energy Management Program* (NIST Handbook 135 2020 Edition). https://nvlpubs.nist.gov/nistpubs/hb/2020/NIST.HB.135-2020.pdf

Kneifel, J., Webb, D., & O'Rear, E. (2016). Energy and Economic Implications of Solar Photovoltaic Performance Degradation. *Special Publication (NIST SP)-1203*.

Lavappa, P. D., & Kneifel, J. D. (2021). *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2021, Annual Supplement to NIST Handbook 135*. (NISTIR 85-3273-36).

Moore, M., & Viscusi, W. (1990). Models for estimating discount rates for long-term health risks using labor market data. *Journal of Risk and Uncertainty, 3*(4), 381-401.

NAS. (2017). *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Retrieved from http://nap.edu/24651:

OIRA. (2011). *Regulatory Impact Analysis: A Primer*. https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/regpol/circular-a-4_regulatory-impact-analysis-a-primer.pdf: Office of Information and Regulatory Affairs

OMB. (1992). *GUIDELINES AND DISCOUNT RATES FOR BENEFIT-COST ANALYSIS OF FEDERAL PROGRAMS*.

OMB. (2003). *Circular A-4*. https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A4/a-4.pdf

OMB. (2017). *Report of the President's Economic Advisors , Analytical Perspectives*. Retrieved from

Scharff, R., & Viscusi, W. (2011). *Economic Inquiry, 49*(4), 959-972. doi:https://doi.org/10.1111/j.1465-7295.2009.00191.x

SEIA. (2015). Photovoltaic recycling.

United States Government. (2021). *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990*. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government

Warner, J., & Pleeter, S. (2001). The Personal Discount Rate: Evidence from Military Downsizing Programs. *The American Economic Review, 91*(1), 33-53.

Webb, D., Kneifel, J., & O'Fallon, C. (2020). *Developing Cost Functions for Estimating Solar Photovoltaic System Installed and Life Cycle Costs Using Historical Quote Data*. Retrieved from https://doi.org/10.6028/NIST.TN.2113:

Wood Mackenzie, & SEIA. (2021). *Q2 2021 - U.S. Solar Market Insight - Executive Summary*. Retrieved from https://www.seia.org/us-solar-market-insight:

Wright, S., Smithers, A., Warburton, P., Pepper, G., Goldberg, J., Brodie, H., . . . Napier, R. (2011). *Practical History of Financial Markets*. Retrieved from https://www.ebsglobal.net/EBS/media/EBS/PDFs/Practical-History-Financial-Markets-Course-Taster.pdf: