NIST Technical Note XXXX

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

Joshua Kneifel
David Webb
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Present Value of Photovoltaics

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

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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 Douglas Thomas and Dr. David Butry of EL’s Applied Economics Office, Dr. Lisa Ng of EL’s Energy and Environment Division, and Dr. Nicos S. Martys of EL’s Materials and Structural Systems Division.

Aut formation

Josl eifel
Eco
Nat ıstitute of Standards and Technology
Eng ;g Laboratory
100 ı Drive, Mailstop 8603
Gai ırg, MD 20899 8603
Tel.)75-6857
Em: hua.kneifel@nist.gov

Dav ɔb
Eng
Nat ıstitute of Standards and Technology
Eng ;g Laboratory
100 ı Drive, Mailstop 8633
Gai ırg, MD 20899 8633
Tel.)75-XXXX
Em: ın.polidoro@nist.gov

Luk ınoyer
Soft Engineer
Nat ıstitute of Standards and Technology
Eng ;g Laboratory
100 ı Drive, Mailstop 8633
Gai ırg, MD 20899 8633
Tel.)75-XXXX
Em: ın.polidoro@nist.gov

Co s

Lis igures

Lis ables

List ronyms

Ac	Definition
AC	alternating current
AC	atomicity, consistency, isolation, and durability
AE	Applied Economics Office
AE	Annual Energy Outlook 2021
AI	Adjusted Internal Rate of Return
AP	Application Programming Interface
AR	IPCC Fifth Assessment Report
AS	American Society for Testing and Materials
AV	Amazon Web Services
BC	benefit-cost analysis
BE	Building for Environmental and Economic Sustainability
BI	Building Industry Reporting and Design for Sustainability
BI EST	BIRDS Neutral Environment Software Tool
CE	Cumulative Energy Demand
CF	chlorofluorocarbons
CF	Code of Federal Regulations
CC	carbon dioxide
CP	Consumer Price Index
CS	Cascading Style Sheet
CS	comma-separated values
DC	direct current
DC	Department of Energy
DS	Database of State Incentives for Renewables & Efficiency
E3	Economic Evaluation Engine
EI	Energy Information Administration
EL	Engineering Laboratory
EL	EL Data, Software, and Technology
EP	Environmental Protection Agency
EP	environmental product declaration
EU	European Union
GF	greenhouse gases
GU	graphical user interface
GV	global warming potential
HT	Hypertext Markup Language
IP	International Panel on Climate Change
IS	International Organization for Standardization
JS	JavaScript Object Notation
LC	life cycle assessment
LC	life-cycle cost
LC	life-cycle cost analysis

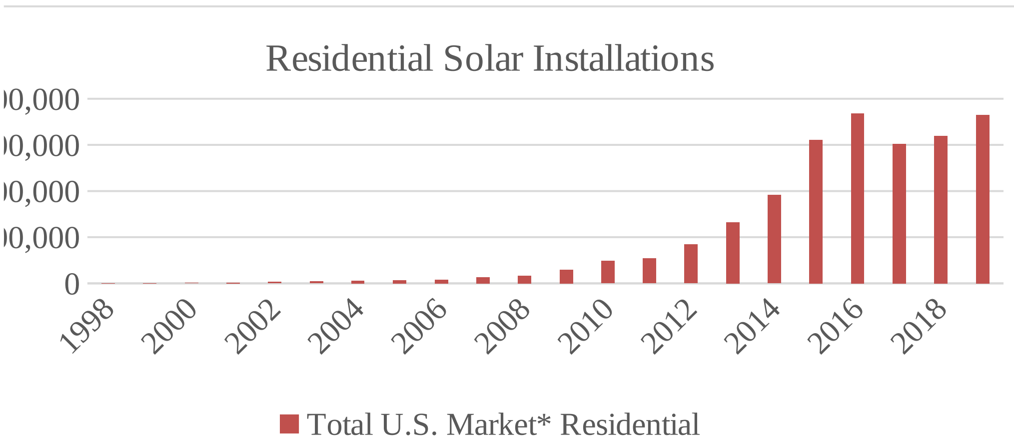
Ac	**Definition**
LC	life-cycle inventory
LC	life-cycle impact assessment
NE	North American Electric Reliability Corporation
NE	National Energy Technology Laboratory
NI	National Institute of Standards and Technology
NC	nitrous oxides
NF	National Renewable Energy Laboratory
NS	net savings
O3	ozone
OF	object-relational mapping

PC	post-consumer
PD	Portable Document Format
PM	particulate matter less than 2.5 micrometers in diameter
PP	power purchase agreement
PV	photovoltaic
RE	representational state transfer
RS	RDF Site Summary or Really Simple Syndication
RV	residual value
SA	System Advisor Model
SC	social cost of carbon
SE	Solar Energy Industries Association
SC	sulfur dioxide
SP	Simple Payback Period
SQ	Structured Query Language
SR	solar renewable energy credit
TR	Tool for the Reduction and Assessment of Chemical and other environmental
VC	volatile organic compound

troduction to [PV][2]

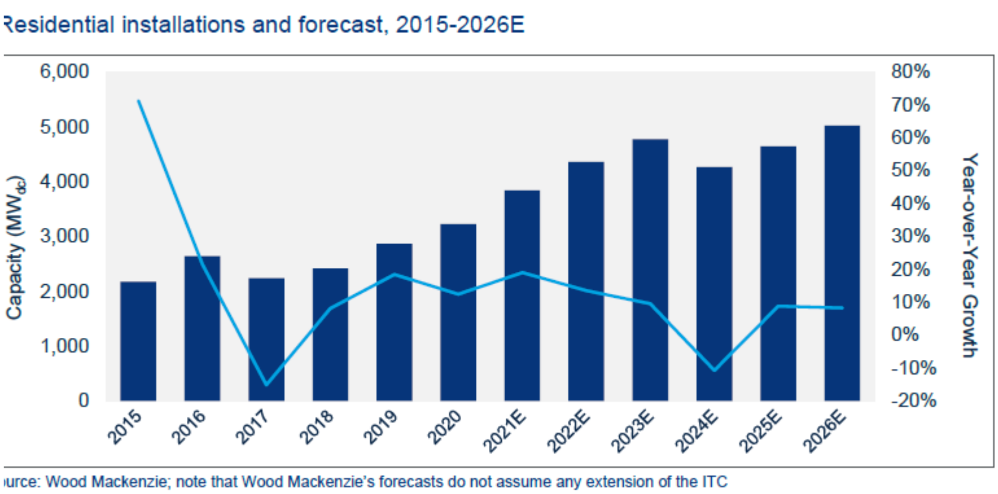
3ackground

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



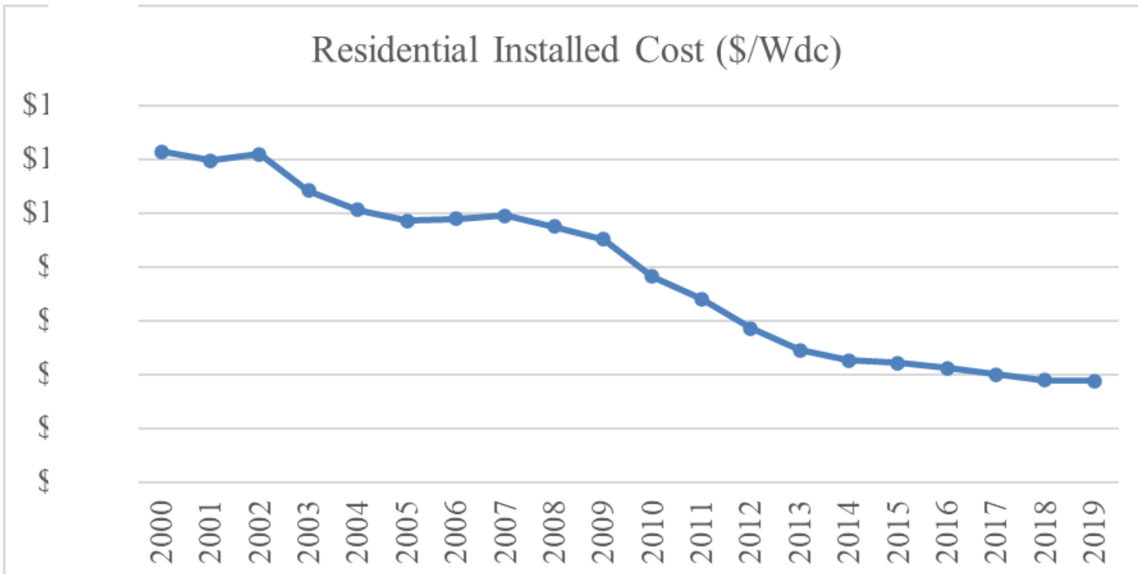
1-1 Residential Solar Installations (Number of Systems) by Year (1998-2019)

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



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

The iver of the increased installation has been the reduction in total installed costs of a hotovoltaic system. Figure 1 -3 shows that the median total gross installed cost att has decreased from over $12/W to less than $4/W. Most of these reductions wer ned by reducing the cost of the photovoltaic module from over $5/W in 1999 dow).44/W in 2019. Inverter costs have decreased from $1.28/W to $0.22/W over the me frame. The remaining costs, which include the BoS and "soft costs" that incl stomer acquisition, permitting, and commissioning, have also seen reductions fror /W in 2000 to $2.96/W (Barbose et al., 2020).



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

Eve e installed cost has decreased by nearly 70 %, the economic and environmental ben d costs of installed rooftop solar photovoltaic systems are difficult for the typi neowner to quantify and evaluate. Each installer may provide different solar tech , brands, and system sizes and configurations. More efficient systems are more cost also more productive. Larger systems tend to have a lower average cost per wat se the marginal cost of installing an additional panel is lower once the crew is alre -site. More complex configurations lead to more difficult installations and, ther igher labor costs. As a result of this variability, a homeowner that receives quo n more than one installer will find significant installed cost price dispersion and ted electricity production (and associated future cost savings) from the quoted syst homeowner must assimilate all this information and select the installer and syst ign that is optimal for their situation. There are other factors that can influence the nics. For example, each state, county, and/or city may have their own inst and operation requirements as well as provide different financial incentives (Gr bates, loan programs, and solar renewable energy credit (SREC) markets).

Sol llers provide some high-level information to the homeowner that can assist in mak eir decision. The quote typically includes gross installed costs, net installed cost ıding available financial incentives), annual and lifetime electricity production, esti ːlectricity cost savings (based on the homeowner's electricity rates), and lifet rbon reductions (using a simple emissions factor). However, the information prov oes not account for discounting or comparisons to alternative investments. Adc ly, solar installers have an incentive to over-estimate the benefits to get an inst ı contract signed. Homeowners are hesitant to trust the installer estimates, mak ː decision even more difficult.

1.2 l of [PV]²

To ; omeowners in making investment decisions related to solar photovoltaic syst ıe Applied Economics Office (AEO) in the Engineering Laboratory (EL) of the Nat ıstitute of Standards and Technology (NIST) developed software, called Pres lue of PhotoVoltaics – [PV]², to analyze the economic and environmental imp ıs of installing rooftop solar photovoltaic systems. [PV]² allows homeowners (anc installers) to complete an independent, transparent, standards-based life-cycle anal a solar installation. Results are provided in easy to understand figures and tabl uding clear reporting of assumptions and the ability to download the data for moı led analysis. The homeowner (or solar installer) need minimal knowledge of life ːost or life cycle assessment methodology to interpret the results. Homeowners can fident that the results from the tool are reliable and transparent, whether con by the themselves or the solar installer.

Suc dependent analysis could be used to answer the following questions, among othe

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

Thi: ical manual documents the development and assumptions used for of the [PV]² wet ation.

1.3]² Performance Evaluation Model

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

Hor ers are increasing interested in the environmental implications of their deci with particular interest in their carbon footprint. However, there are more env ntal impacts from our decisions than climate change, such as ozone depletion and creation. Considering multiple impacts across all stages of the life cycle is nec ecause decisions based on one criteria or life cycle stage could obscure othe might cause equal or greater damage.

For le, the electricity generation from a solar photovoltaic system produces zero emi Each unit of solar-based electricity reduces a unit needed from the electric grid current comes from a mix of fuel sources including some percentage of foss . The result is a reduction in emissions of not just carbon, but also other harı nission such as particulate matter that can increase asthmatic attacks. Hov it is necessary to include environmental impacts resulting from the mar ring of the solar photovoltaic system as well as the disposal of the system at the its service life.

Wh ironmental performance typically cannot be measured on a monetary scale, it can ntified using the multi-disciplinary approach known as environmental Life Cyc essment (LCA) that addresses multiple impact categories over multiple life cycl s. The BEES methodology measures environmental performance using LCA, foll guidance in the International Organization for Standardization (ISO) 14040 and 140 dards for LCA (International Organization for Standardization (ISO), 2006a, 200

1.4 rmation Required by [PV][2] from the User

[PV ires minimal information from the user to complete an analysis. The user only nee ovide information on their location, electricity costs, solar photovoltaic system deta sts, and production, available financial incentives, and the state's SREC mar ost installers will request and/or supply this information for their own calc s as part of their solar installation quote.

The owner must provide the address of the home on which the solar will be inst his information is required because the grid-sourced electricity emissions rates var cation. Each ZIP code is mapped to the Balancing Authority in which it is loca oogle Maps is leveraged to assist in populating the address information.

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

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

The ɾovides default values for the “Advanced” parameter options, such as equ services lives, energy escalation rates, and solar photovoltaic panel efficiency deg n rate. These underlying assumptions can be viewed and modified by the user. Hov changing these values is only recommended for user with a clear understanding of tl rameters. Additional details on the advanced parameter default values and data sou ɛ discussed in Section 3.4.

1.5 Data Inputs and Results Security in [PV]²

[PV not save any data inputted by a user or any of the results once the user closes or r s the webpage including the results spreadsheet (CSV) file and results PDF Rep e user can save their results if desired. The user can use the “Back” arrows with tool (NOT the web browser navigation) to make changes to an analysis and reru results without having to start over.

2 Selections and Parameter Definitions

2.1 ding Page

A u access [PV]^2 at its landing page: www.nist.pv2.gov. The landing page shown in F 2 -4 provides the user with a summary description of the tool and a "Start" butt egin an analysis. Additional information is provided for the Economic Eva Engine (E3) that handles the back-end calculations provided by [PV]^2 and the Met d Tools for Sustainable Buildings Project that funded the development of this soft he header on each page provide links back to this homepage as well as to a usei and (forthcoming) tutorial. There is also a link to an example solar installer proj ıd electric utility bill (labeled "Example").

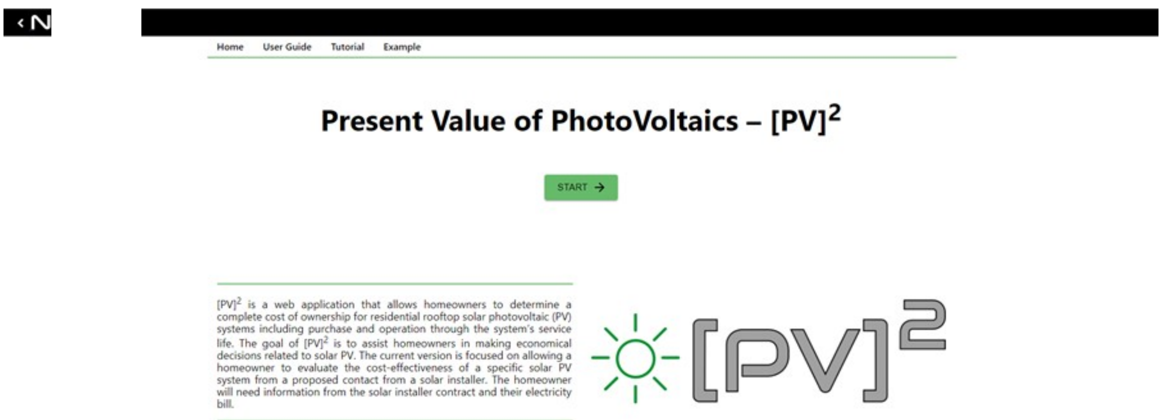


Figure 2-4 [PV]^2 Landing Page

2.2 ress

The ıge of [PV]^2 is the "Address" page shown in Figure 2 -5 on which the user can e the address (street, city, state, and ZIP code) of the home on which the solar pho ic system may be installed. The user can start by typing in the street address and ıogle Maps plug-in should automatically zoom to the location. For users that are ıed about sharing their specific address, the address is optional with only the ZIP ıeing required.

The ıde is the only value that is required for [PV]^2 to complete an analysis because it is ı find the associated environmental data related to electricity consumption in that ın. Once the ZIP code has been entered, the user can then click on the "Next" butt o to the "Analysis Assumptions" page.

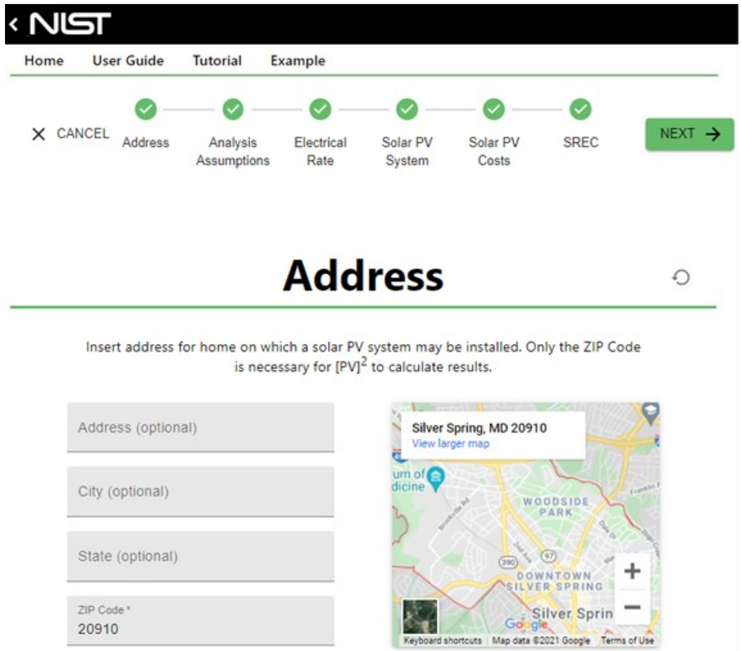


Figure 2-5 Address Page

2.3 lysis Assumptions

The ysis Assumptions" page shown in Figure 2 -6 requires the user to input some gen onomic assumptions: study period, real discount rate, and general inflation rate. Tw s are currently hidden from the user and defaulted to the only option currently avai residual value approach and electric grid fuel mix. Both the user inputted and def assumptions are used for completing the economic analysis. Each of these par is defined in Table 2 -1. Default values are provided for users if they are unc what value to input.

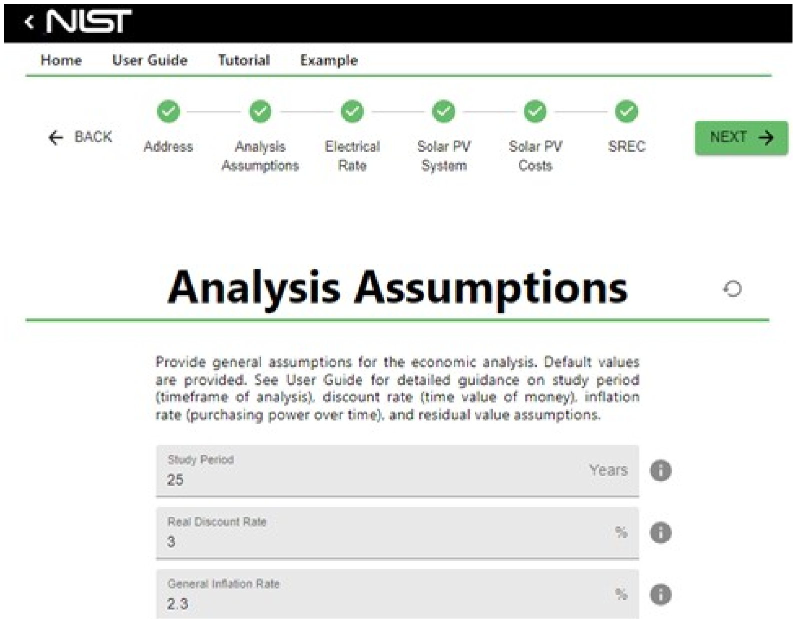


Figure 2-6 Analysis Assumptions Page

Tal Analysis Assumptions

An As ns	**Definition**	**Valid Values and Unit**
Stu d	Study period is the length of the time covered by the economic evaluation	1-40 years
Re: rate ınt	Real Discount Rate reflects the Time Value of Money apart from changes in the purchasing power of the dollar (i.e., general inflation)	%
Ge infl :e	General inflation rate is the rate of rise in the general price level.	%
Re: app ılue	Residual Value is the estimated value of the system at the end of the study period	Linear Depreciation *Remaining Production Value*
Ele Fue d	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)*
Ita ems are not in the current version of [PV][2]		

The period is the length of the time covered by the economic evaluation and is limi ıo more than 40 years. The recommended study period is the estimated service life ;olar photovoltaic system (specifically the solar panels). A common practice is to u ength of the warranty on the solar panels as the study period. Additional info n on study periods is provided in Section 3.1.

The scount rate is the time value of money apart from changes in the purchasing pow ie dollar (i.e., general inflation). The basic concept is that a dollar now is worth mor u than a dollar a year from now. There is an opportunity cost for waiting to rece yment of that dollar. The rate of increase in that payment that makes someone indi to receiving a dollar now versus that larger payment (dollar plus interest) next yea ır discount rate. The real discount rate assumes that the purchasing power of a doll ains constant. The real discount rate will vary by user and depends on the use best alternative investment. For example, the long-term average real rate of retu quities is 7 % (CITE) while investing in 30-year treasury bonds provides a real retu pproximately 0 %. In most cases, a user will know their nominal discount rate, whi udes inflation. The formula for calculating the real discount rate from the nom scount rate and general inflation rate is: $d = \frac{1+D}{1+I} - 1$. An example of a nominal disc ıte is a user's current mortgage rate if the additional money would otherwise be use y down the mortgage balance instead of purchase the solar photovoltaic system. The vould input the nominal discount rate and the inflation rate into the formula to get l discount rate. Additional information on discount rates is provided in Section 3.3.

The ıl inflation rate is the rate of rise in the general price level, or, put another way, a de ı the general purchasing power of the dollar. The Federal Reserve's target infl ıte for the U.S. is 2.0 %. Additional information inflation is provided in Section 3.3.

Res alue is the estimated value, of the solar photovoltaic system remaining at the end study period, net of any disposal costs. The value could be obtained from resa ılvage of the system or from keeping the system operational for the remainder of it ce life after the study period ends. The linear depreciation approach is the only opti ently available for users. This approach assumes that the residual value is a line tion of the installation cost for an investment. Note that if the study period and the life of the solar photovoltaic system are the same, the residual value will be zero lternative approach, Remaining Production Value, will be discussed in Section 3.2. lection of the residual value approach is currently hidden from the user.

Ele id fuel mix is the assumed fuel mix used for the electricity consumed in the buil location, which is mapped to the balancing authority. The fuel mix assumption is u select the LCA data for electricity in the location. Additional details on the LC are discussed in Section 4.5. The three options that will be included in the offi rsion of [PV][2] are as follows:

- **mark** assumes the current electricity fuel mix remains constant over time on the most recent available data (currently 2018)

- **tion – Baseline** assumes the electricity fuel mix changes over time based on O2021 Reference case, which has increases in natural gas and renewable y over time
- **tion – High Renewable** assumes the electricity fuel mix changes over time on the AEO2021 Low Renewable Cost case, which leads to greater renewable capacity than the AEO2021 Reference case

Cur [PV][2] defaults to Benchmark, and the selection is hidden from the user.

2.4 trical Rate

The rical Rate" page shown in Figure 2 -7 requests that the user to input the ann ctricity consumption, demand charge, consumption rate, whether its net met r gross metering, production rate, and photovoltaic grid connection fee. Add ly, the user can view or edit the assumed electricity price escalation rates. The es are used to calculate the electricity costs and savings over the study period. Eac ese parameters is defined in Table 2 -2. Default values are provided for users if th uncertain what value to input.

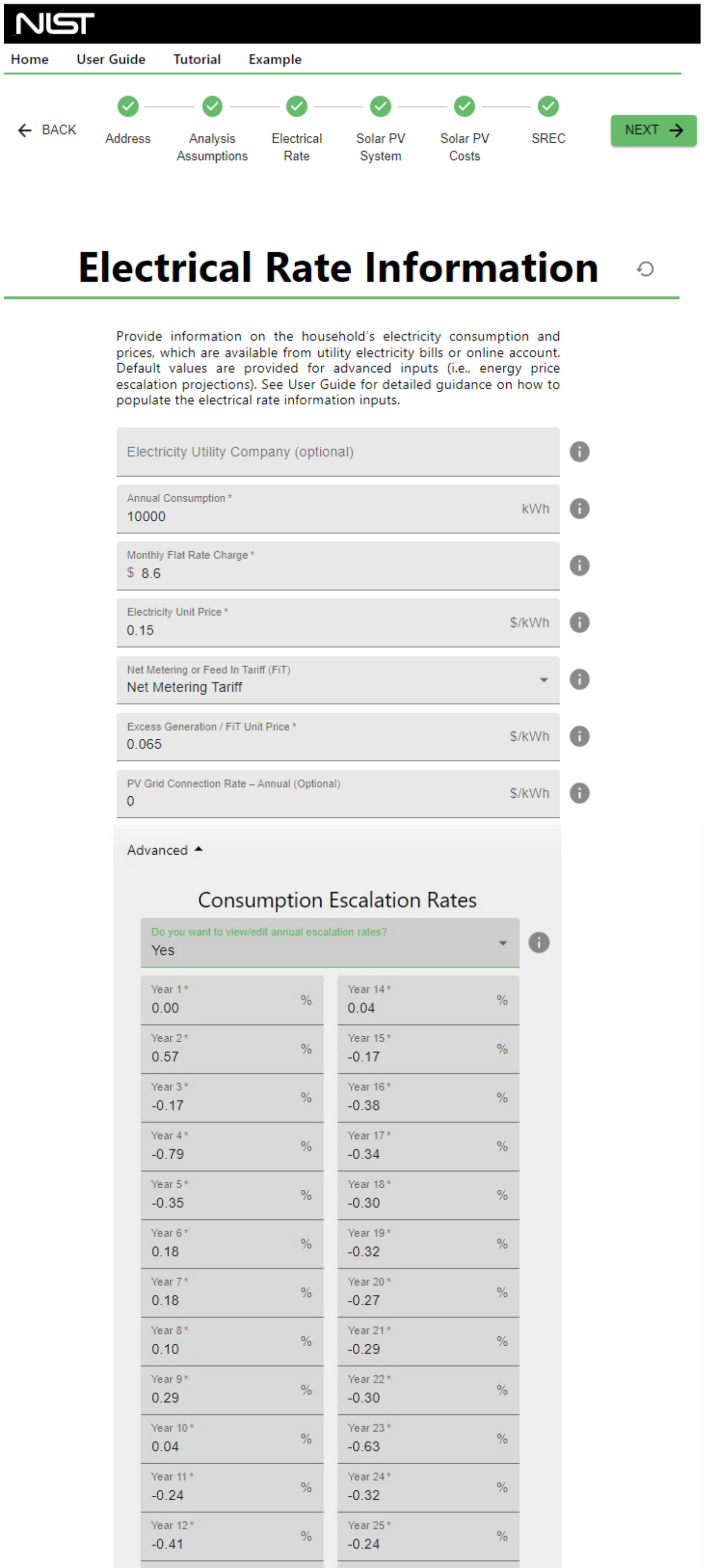


Figure 2-7 Electrical Rate Page

Tal Electrical Rate

Sol ystem	Information Icon	Unit
Ele lity Na	Electricity Provider Name.	Not Applicable
An Co on	Annual electricity consumption of the household.	kWh
De arge	Demand charge is a fixed cost for having an electricity provider account.	$
Co on Rate	Cost per unit of electricity consumed ().	$/kWh
Ne s Me	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
Pro 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 Co Fee	Annual charge for connecting a solar PV system to the grid. This value is often zero ($0).	$
An alation Ra)	Annual escalation rates for electricity prices.	%

The city provider name is optional and currently for informational purposes only.

Anr sumption is the annual electricity consumption of the household (kWh). A user se the previous year's bills or obtain consumption data from the users online acc r the electricity provider.

The ly Flat Rate Charge is a fixed cost for having an account and can be found on mor ectricity bills or from the electricity providers rate schedules.

Elec Unit Price is the cost per unit of electricity consumed ($/kWh) is the sum of all cost iated with a unit of electricity (i.e., marginal costs), such as generation, tran on, and distribution charges, taxes, fees, environmental fund payments.

Net ng means that the homeowner is charged (or paid) for the net difference in elec consumption and electricity production. Typically, the price paid for excess con on is different (usually higher) than the price paid to the homeowner for excess proc .

Gro ering (i.e., feed-in tariff) means that the homeowner is paid for all production and ged for all consumption, typically at different rates.

Exc neration / FiT Unit Price is the price paid per unit of electricity proc generated ($/kWh), which is typically different than the Electricity Unit Price. Und metering, the user provided value is applied to excess annual generation (ann neration greater than annual consumption). It is common for this value be set to tl of the utility's marginal generation charges, and excludes costs such as dist 1, transmission, taxes, and fees paid on grid-based electricity provided by the utili ne Excess Generation Price cannot be determined, it is reasonable to use the gen charge per kWh provided on the electricity bill as a reasonable estimate. For gros ring (i.e., FiT), the user provided value is applied to all electricity generation. In tl e the grid-based electricity costs and the payment received for solar PV system gen are independent of each other. If a user cannot determine the Excess Ger 1 / FiT Unit Price, it is reasonable to assume it is equal to the Electricity Unit Pric

PV onnection Fee is the annual charge for connecting a solar PV system to the grid value is typically zero ($0) and, thus, treated as an optional value.

Ann calation rates are the rate of change for electricity prices over time. The default valu based on Energy Information Administration (EIA) projections for each Cen gion and published in the Annual Supplement to NIST Handbook 135 (add hyp . These values are non-constant and are applied to both the prices for con on from the electric utility and excess production for which the homeowner is paid user can modify the escalation rates and make the escalation rates for electricity con on different than the escalation rates for excess production.

2.5 r PV System

The PV System" page shown in Figure 2 -8 requires the user to input a system desc 1, solar panel rated efficiency, inverter type, system size, and estimated annual prod . Additionally, the user can view and modify the panel lifetime, inverter lifet nd system production degradation rate. These values are used to calculate the elec production and associated electricity cost savings, and potential replacement cost esidual value related to the system. Each of these parameters is defined in Tab 3. Default values are provided for users if they are uncertain what value to inpu

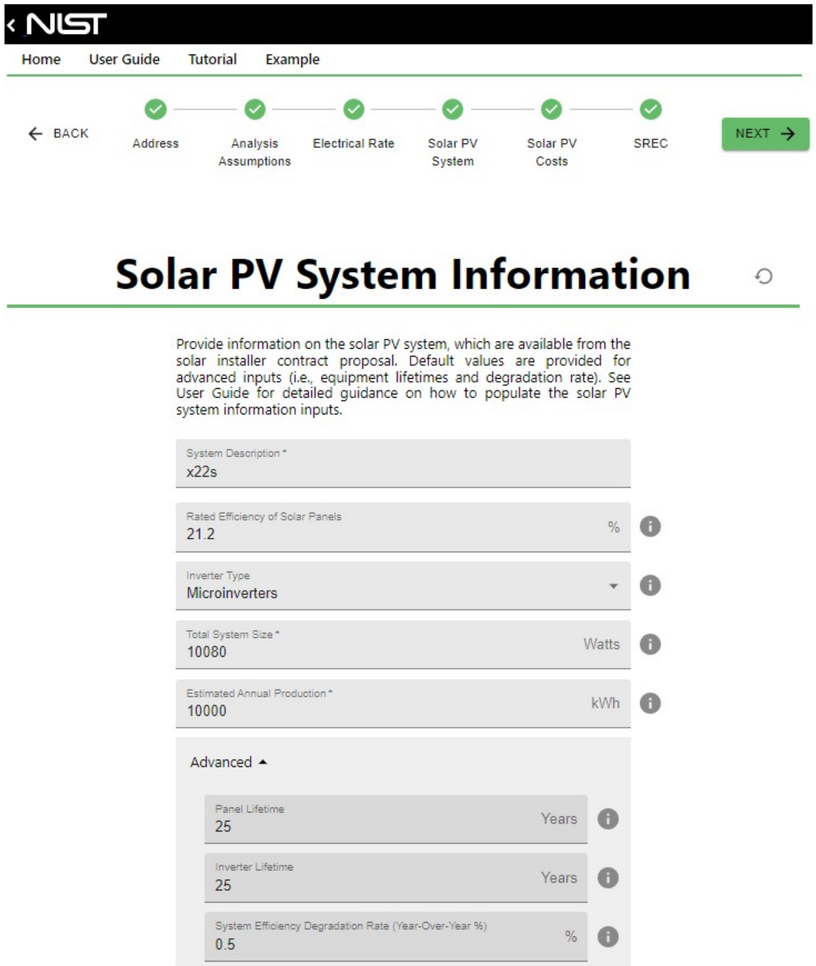


Figure 2-8 Solar PV System Page

Tal Solar PV System

Sol ystem	**Information Icon**	**Valid Values and Unit**
Pa d / Type	Solar Panel Brand / Type is currently used for informational purposes.	Not Applicable
Sol Rated Eff	Solar Panel Rated Efficiency is the rate efficiency on of the solar panels on the panel specification document/installer literature	15 % to 25 %
Inv pe	Inverter technology type: Microinverter, String, or String with Optimizers	Not Applicable
Sys e	Total rated capacity of the solar photovoltaic system	W_{dc}
Est Annual Prc	Estimated annual production in the initial year of operation.	kWh
Pa ne	Panel lifetime is the expected service life of the solar panels.	1 Year to 40 Years
Inv time	Inverter lifetime is the expected service life of the inverters.	1 Year to 40 Years
De rate	Degradation Rate is the rate at which the solar production decreases each year. Default is 0.5%.	%

The n description is used for the title of the system being analyzed, and can assist a user comparing more than one analysis report from the software. For example, a user label the system by some combination of solar installer and system spec ons.

The panel rated efficiency is used for matching to the solar panel LCA data, which vari quality category (combination of type, efficiency, and warranty). Solar Panel Rat ciency is the rate efficiency on of the solar panels on the panel specification doc installer literature, which will typically range from 16 % - 22 %.

The er type can be microinverter, string, or string with optimizers.

Esti annual production is the production in the initial year of operation.

Pan me is the expected service life of the solar panels, which is typically 25 years (cor warranty length) and must be 40 years or less.

Inve etime is the expected service life of the inverters and must be 40 years or less. Typ etimes by inverter type are 15 years or length of the warranty for string inve with or without optimizers) and lifetime or warranty length of panels for mic ters.

The ations in [PV]^2 account for decreasing production due to efficiency degradation of t r photovoltaic system. Degradation rate is the rate at which the solar pro decreases each year. The default degradation rate is 0.5%, but specific system deg n should be available in the solar photovoltaic system's warranty document.

2.6 r PV Costs

The PV Costs" page shown in Figure 2 -9 requires the user to input solar pho ic system cost and purchase details. For system costs, the user must provide the stallation costs and value of state/local financial incentives (grants or rebates). The as the option under "Advanced" to view and modify the inverter replacement cost nnual system maintenance costs.

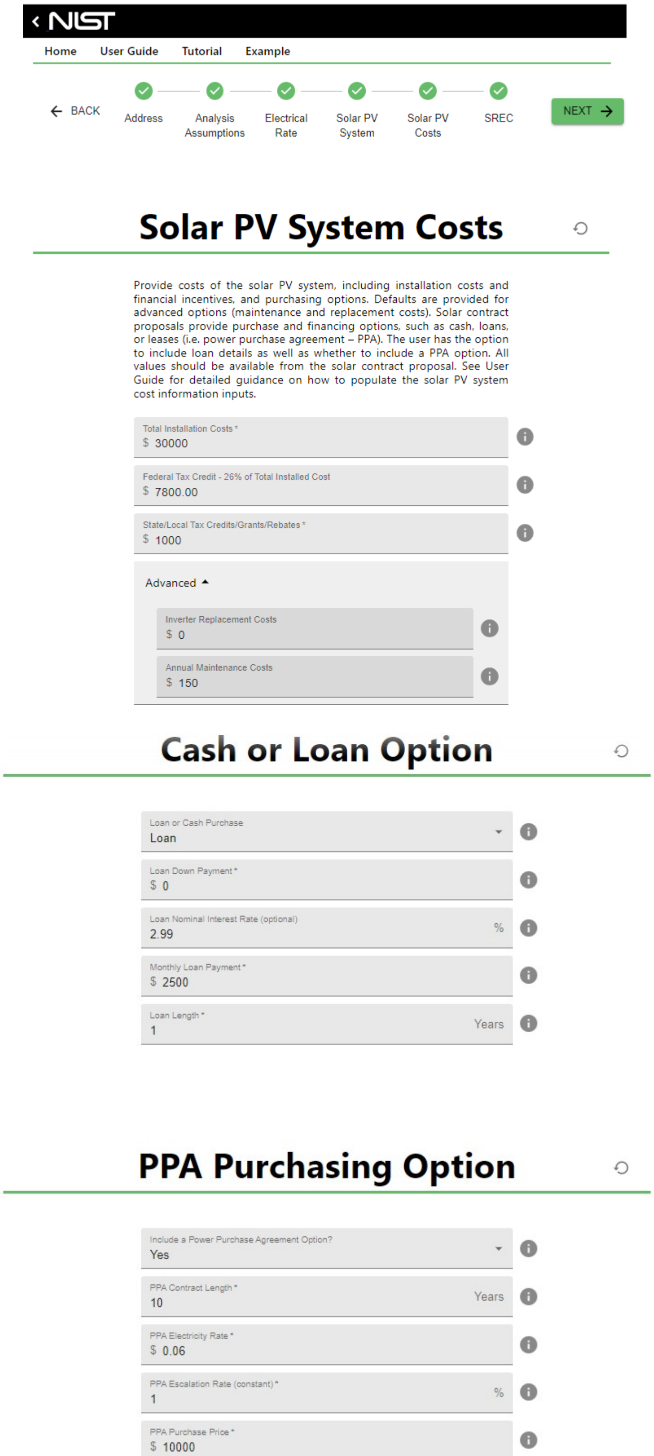


Figure 2-9 Solar PV Costs Page

The an choose between a cash purchase and financing through a loan. If the pur(ype is a loan, the user must provide the down payment, loan length, and mo1 ayment, which is commonly provided in the solar installer proposal. A user is also led the option to include a power purchase agreement (PPA) option (i.e. lease) to tl [illegible] ysis, which may be offered by some solar installers. If a lease/PPA option is incl [illegible] he user must provide the contract length, initial electricity rate (i.e., price), elec [illegible] price escalation rate, and system purchase price at the end of the contract. Each of tl [illegible] rameters is defined in Table 2 -4. Default values are provided for users if they are [illegible] ıin what value to input.

Tal [illegible] Solar PV Costs

Sol [illegible] ystem	Information Icon	Valid Values and Unit
To [illegible] lation Co [illegible]	Total (gross) costs of installing the system.	$
Fe [illegible] edit	Federal tax credit is currently 26% of total installation costs.	$
Sta [illegible] Gr [illegible] ates	State and local financial incentives include grant and rebate programs.	$
Inv [illegible] lacement cos [illegible]	Costs of replacing only the inverters.	$
An [illegible] ntenance cos [illegible]	Annual costs of maintaining the solar PV system	$
PP [illegible] ı	Include a PPA/leasing option in the analysis.	YES / NO
PP [illegible] ıct Length	Length of PPA/Lease Contract. 40 years or less.	1-40 Years
PP [illegible] icity Rate	Price of electricity produced by solar PV system.	$
PP [illegible] ıtion Rate (co [illegible]	Rate at which the price of electricity from solar PV system increases year-over-year.	%
PP [illegible] ıse Price	Cost to purchase system at the end of the contract.	$
Lo [illegible] sh	Choose between purchasing upfront ("cash") or through financing (loan).	Not Applicable
Do [illegible] ıent	Percent of Total Installed Cost Paid at Time of Signature/Installation.	$
No [illegible] terest rate	Nominal interest rate on the loan.	%
Mc [illegible] yment (op [illegible]	Monthly payment on the loan.	$

Tot [illegible] llation costs are the total (gross) costs of installing the system before financial ince [illegible] such as federal tax credits and state/local grants or rebates. The user should excl [illegible] y costs for re-roofing because that is treated as an independent decision. The fed [illegible] credit is currently 26% of total installation costs. This credit applies to all cost [illegible] iated with the installation. The value is automatically calculated by [PV][2] usir [illegible] ax credit rate and the total installation costs. State and local financial incentives incl [illegible] ınt and rebate programs. These should be summed and included as a single val [illegible] e that loan-based solar programs (often labeled as financial incentive policies) will [illegible] lressed under Purchasing Details below. Inverter replacement costs are the cost [illegible] placing only the inverters. The value should only be provided if the inverter's exp [illegible] ervice life is not the same as the solar panels. Annual maintenance costs are the ann [illegible] ts of maintaining the solar PV system, such as annual contract with installer to clea ls and check panel performance. These costs tend to be minimal for most syst

The r loan decision is a choice between purchasing upfront (“cash”) or through fina loan). In the case of a loan, the down payment is the percent of total installed cost t the time of signature or installation. Down payments typically range from 0 % %. The nominal interest rate is the interest rate paid on the loan while the mor ayment is the amount paid each month on the loan. Note that the interest rate is opti ad for informational purposes only.

In tl that a solar photovoltaic system is installed through a PPA or lease, the inst vns the system and homeowners sign a contract to pay the installer for the elec produced by the system. Typically, homeowners have a purchase option at the end contract, which can vary in length, but typically will not extend beyond 25 yea s limited to 40 years or less in [PV][2]. PPA electricity rate is the price of elec produced by solar photovoltaic system under the PPA. Typically, this price is less rice paid to electricity provider for grid-sources electricity. PPA escalation rate is th at which the price of electricity from solar PV system increases year-over-year, whi ssumed to be constant. The PPA purchase price is the cost to purchase the syst he end of the contract. The assumption is that the system is purchased, and all proc from the photovoltaic system after the end of the contract through the end of the eriod is owned by the homeowner.

2.7 C – Solar Renewable Energy Credit

The C” page shown in Figure 2 -10 requires the user to select the type of SREC pay nd the value of those payments. These may include a single up-front payment or f ayments based on production. Each of these parameters is defined in Table 2 - 5. V are defaulted to zero.

Sol ewable Energy Credits (SRECs) are not available in all states. Therefore, there will value to a homeowner in most states. If an SREC market does exist in a user’s loca hen there are typically two options for monetizing those values, either through up-f future payments. Selecting an up-front payment means the rights to the SRI sold upfront in a lump sum value based on rated capacity ($/kW). Selecting proc -based payments means that payments are made every 3 months based on proc from the system ($/MWh). The user must provide the expected value of future SRI ments for each year of the study period. There is variability and uncertainty in the ed value of SRECs in the future as well as actual production. Therefore, SREC agg s provide production-based contract that guarantee a value of those SRECs (at a di to current SREC market prices).

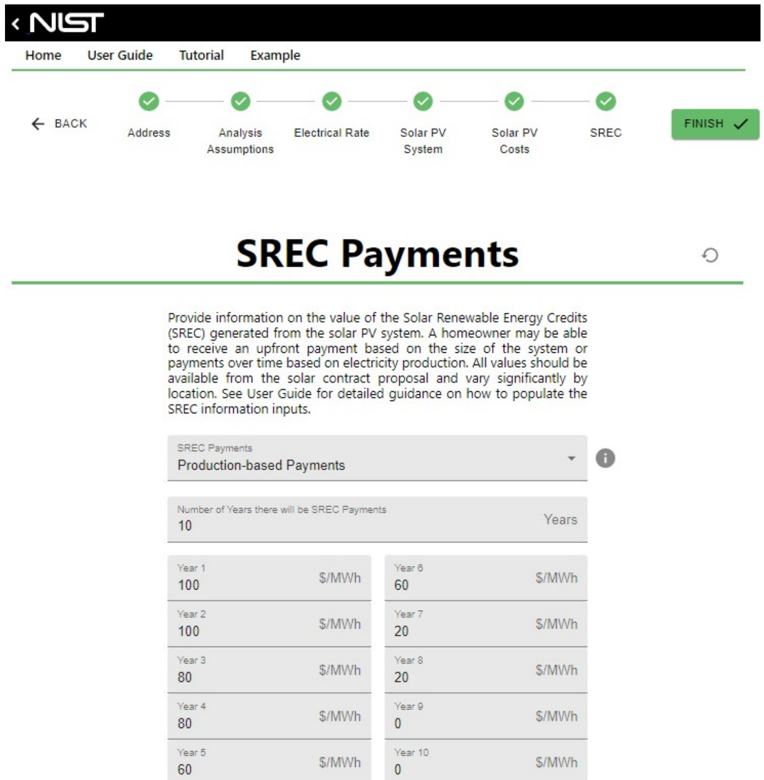


Figure 2-10 SREC Page

Tal SRECs

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

2.8 ılts

The lts" page shown in Figure 2 -11 and Figure 2 -12 provide the user with the ecoı and environmental performance of two alternatives (or three alternatives if a PPA ı was included as in the displayed example). The results provide a system sum results summary, graphs, and the user's input assumptions used in the analysis. The an also download the results in spreadsheet (CSV) format or in a PDF Report usir lownload buttons on the top right of the results page.

The ile includes:

- summary table
- summary table
- NPV cash flows by alternative table

The Report includes:

- summary table
- summary table
- tive NPV cash flow graph
- ssumptions lists

The summary includes the system description, size, efficiency, and equipment lifet s well as the initial costs (installation costs and financial incentives). The resu mary includes economic, environmental, and electricity performance. The eco measures provided are total NPV costs, net savings, adjusted internal rate of retu RR), and simple payback period (SPP). The electricity reduction measures are tota based electricity consumption reduction and percent electricity reduction. The env ntal measures include Carbon Footprint - global warming potential (GWP) in carb xide equivalent (CO_2e) greenhouse gas emissions (GHG) emissions - and total exte costs from those GHG emissions (i.e., Social Cost of Carbon). Note that [PV][2] curr rovides one environmental impact category (GWP), but includes calculations for nvironmental impact categories associated with the solar photovoltaic system that e included in results reporting in the official release of [PV][2]. Each of these mea re defined in Table 2 -6.

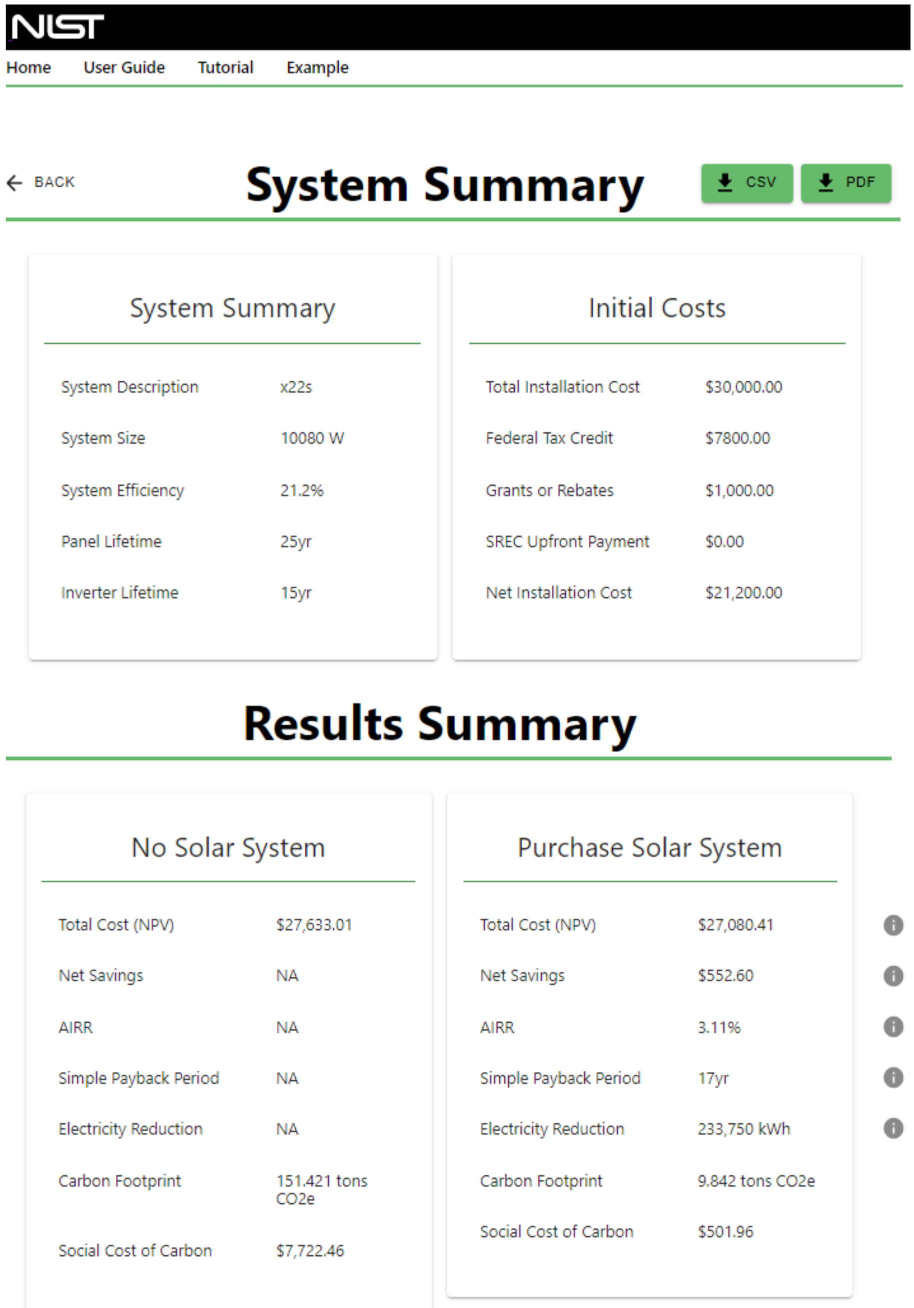


Figure 2-11 Results Page Summary Information

Tat Results

Re		Description	Units	Reported
To		Total Net Present Value Costs	$	YES
Ne	s	Net savings (NS) is Net Present Value Cost Savings relative to No Solar System	$	YES
AI		Adjusted Internal Rate of Return (AIRR) on Investment	%	YES
SP		Simple Payback Period (SPP)	Years	YES
Ele	Reduction	Electricity reduction relative to No Solar System	kWh	YES
Per Re	ctricity	Percent reduction in electricity consumption relative to No Solar System	%	YES
Ext Soc	Costs – of Carbon	The Social Cost of Carbon is the negative impact, in dollar terms, of greenhouse gas (GHG) emissions	$	YES
GV		Global Warming Potential	CO2e	YES
To	ry Energy	Total primary energy consumption	MJ	NO
Re	Effects	Respiratory effects	PM2.5e	NO
Oz	letion	Ozone Depletion	CFC-11e	NO
Sm		Smog formation	O3	NO
Ac	on	Acidification potential	SO2e	NO
Eu	ion	Eutrophication potential	Ne	NO

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

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

The nmental and social performance is measured with seven life cycle impact asse categories. The three categories of most interest to current decision makers are total primary energy consumption, and respiratory effects. GWP is used to mea e climate change-related impacts. Total primary energy consumption includes all associated with both the grid-based electricity reduced as well as the embodied ene he solar photovoltaic system. The broader perspective on energy consumption

pro' more complete perspective on the life cycle implications of installing sola
pho ics. Respiratory effects measure particulate matter and air emissions that may
resu ealth issues such as asthma and other respiratory illnesses. The other four
imp egories are ozone depletion, smog formation, acidification potential, and
eutr tion potential. Currently, only GWP is reported, but results could be expanded
to o pact categories if determined that the additional information would be worth
the complexity for users. All impact categories are discussed in more detail in
Sec 3.

The cost of carbon (SCC) is the estimated impact, in dollar terms, of greenhouse
gas) emissions on society. The value is set to \$51/ton of CO_2e emissions and
app all GHG emissions as measured in the GWP impact category (includes
emb emissions in the solar photovoltaic system and the reduction in grid-provided
elec consumption). SCC is discussed in more detail in Section 3.5.1.

Alo n the summary results provided in tables and figures, the user can print the
sum esults and/or download the data to develop their own data analysis that the
curr l does not provide. For example, the user may want to compare the relative
perf ce of two different solar photovoltaic systems. If the baseline case is the same,
a us either manually compare the results across printed results or create their own
syst nparison in a spreadsheet.

The s section of the results shown in Figure 2 -12 allow a user to view net present
valu ear for annual cash flows, annual net savings, and cumulative net savings
(sho re) as well as annual net electricity consumption and cumulative net electricity
redu In this example, purchasing the system has high initial costs that are overcome
ove o lead to significant cost savings by the end of the 25-year study period.
Sim the PPA option also leads to significant cost savings but with no initial costs.
Bot natives are preferred to not installing a solar photovoltaic system.

The nputs" section shown in Figure 2 -12 allows the user to quickly review their
inpu l in the analysis. This may allow a user to identify a mistake in their inputs or
valu y may want to alter to see how the results change.

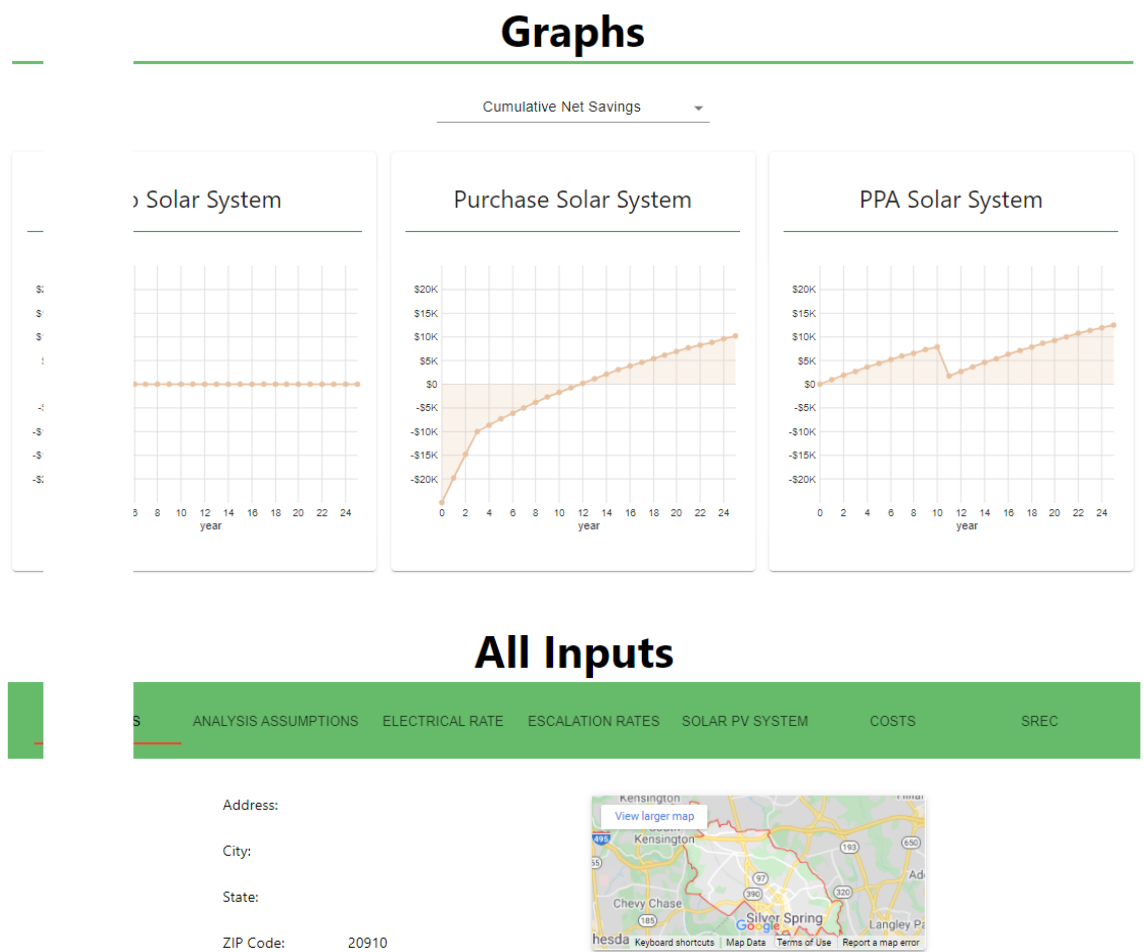


Figure 2-12 Results Page – Graphs and Inputs

Alo ı the summary page, the user can download the results in a PDD-formatted Anε .eport that provides the same summary information, cumulative savings figure, and ·f analysis assumptions. The initial page of the report, shown in Figure 2 -13, has esigned based on solar installer proposals that provide similar information to pote ıstomers, including system information, initial cost and financial incentives, and ary economic and environmental results by alternative. The other two pages of the ɔrovide all input assumptions to provide transparency on the analysis.

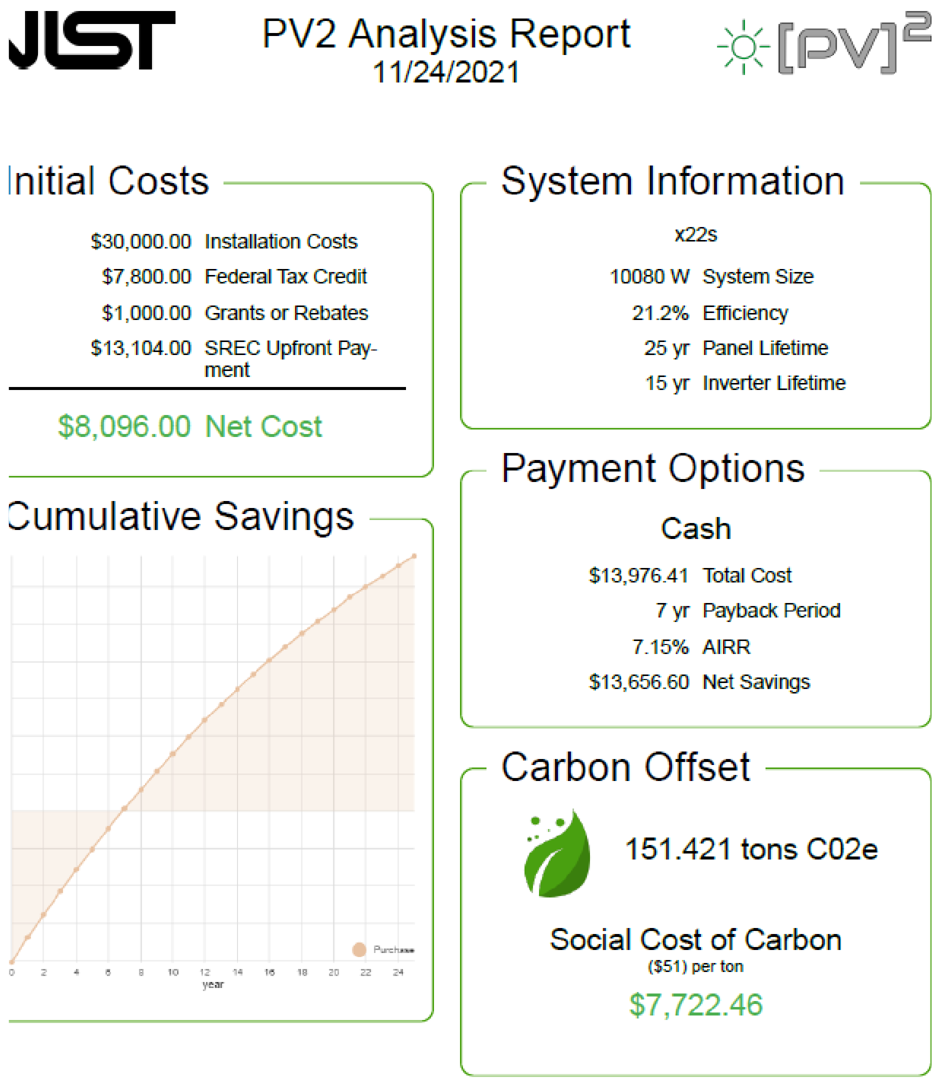


Figure 2-13 PDF Results Report Example Summary Page

2.9 ing an Analysis

The an edit their analysis assumptions by using the Back button on the Results pag er should save the PDF or CSV files for an analysis that they want to compare to fu ›sults before changing any assumptions. All user inputs are saved in the tool unti ›er closes the browser window or returns to the [PV]² main page. The user can edit lual input values one-by-one to fix a mistake or test how changing one value will t the results. A user can also reset entire sections on an input page by using the “Re)efaults” button (i.e., gray circle arrow) at the top right of every input section, whi ' be useful in evaluating a different proposal for the same system or a different sola ›voltaic system proposal from the same installer.

3 omic Performance Evaluation

Mea the economic performance of solar photovoltaic systems is relatively stra ward. Cost data are readily available from the solar installer and the electricity prov nd there are well-established ASTM standard methods for conducting econ performance evaluations. The most appropriate method for measuring the econ performance of building products is the life cycle cost (LCC) method (Joshua Kne Webb, 2020). [PV][2] follows the ASTM standard method for life cycle costing of b -related investments (ASTM, 2017).

3.1 ly Period

It is tant to distinguish between the time periods used to measure environmental perf ce and economic performance. These time periods are different. Recall that in env ntal LCA, the time period begins with raw material acquisition and ends with prod d-of-life. Economic performance, on the other hand, is evaluated over a fixed peri own as the study period) that begins with the purchase and installation of the prod d ends at some point in the future that does not necessarily correspond with prod d-of-life.

Eco performance is evaluated beginning at product purchase and installation beca is is when out-of-pocket costs begin to be incurred, and investment decisions are ased upon out-of-pocket costs. The study period ends at a fixed date in the futu ch could vary based on the homeowner's expected number of years owning the If the homeowner expects to sell the home before the end of solar pho ic system's service life, the study period length could be set at the period of hom ership. If the homeowner expects to be a long-term owner of the home, the stud d length could be set at the useful life of the longest-lived product alternative (i.e. panel service life).

In [conomic performance is measured over a study period defined by the user up to 4 s. Solar photovoltaic panels typically have a warrantee of up to 25 years. How as more long-term installation performance data have become available, some inst re beginning to claim the potential for a 40-year service life. Additionally, ther no available projections for energy prices beyond 40 years into the future. The the maximum study period allowed is 40 years.

3.2 Cycle Costing

The method sums over the study period all relevant costs associated with each alte to meet the household's electricity demand. Alternatives can then be com based on their LCCs to determine which is the least cost means of fulfilling the ity demand over the study period. Categories of cost typically include costs for se, installation, operation, maintenance, repair, and replacement. The costs asso with the initial purchase and installation and any replacements that occur ove study period are based on the defined system service life. The cost of equ replacements is assumed to be the same as the initial purchase and inst costs. Annual maintenance costs are assumed to ensure no repair costs occ residual value is the value of the product remaining at the end of the study peri is, therefore, a negative cost value. In [PV]^2, the residual value is computed for t equipment installation by prorating the purchase and installation cost over the t life remaining beyond the 60-year period (linear depreciation approach). An alte residual value approach is the estimated value of the electricity production fror emaining life of the solar photovoltaic system.

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

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

Wh *st = Costs of initial purchase and installation*
ture = Present Value of replacement costs
= Residual Value of last product installation

3.3 ount Rate and Inflation

The nethod accounts for the time value of money by using a discount rate to con future costs to their equivalent present value. Future costs must be expressed in te nsistent with the discount rate. There are two approaches. First, a *real* disc ite may be used with constant-dollar costs. Real discount rates reflect the port the time value of money attributable to the real earning power of money over time ot to general price inflation. Even if all future costs are expressed in constant doll ey must be discounted to reflect this portion of the time-value of money. Sec *market (nominal)* discount rate may be used with current-dollar amounts (e.g., actu re prices). Market discount rates reflect the time value of money stemming fror inflation and the real earning power of money over time. When applied prop both approaches yield the same LCC results. The [PV]^2 model computes LCCs usir tant dollars and a real discount rate. This section provides background on pote iscount rate and inflation rate values and how the default values were sele

3.3. count Rate

As lt, [PV]^2 offers a real rate of 3.0 %, the 2021 real discount rate for DOE ene ciency, water conservation, and renewable energy project evaluation (La & Kneifel, 2021) and the “social rate of time preference” (OIRA, 2011; OMB, 200

Lav nd Kneifel (2021) sets the real discount rate at 3 % based on the process defi 10 Code of Federal Regulations (CFR) 436, which is the higher of two valu The real discount rate calculated using long-term Treasury Bond rates ave ver 12 months and the general inflation rate published in the Report of the Pres s Economic Advisors, Analytical Perspectives (OMB, 2017) or (2) a pres floor of 3 %. The calculated real discount rate has been lower than the pres floor of 3 % for the past 10+ years.

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

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

Anc ternative is the "historical average before-tax rate of return to private capital
in tl economy," which Circular A-4 estimates to be 7.0 % (OMB, 2003). This
valu nsistent with what has been termed at "Siegel's Constant" of real returns from
the narket of 6.5 % (Wright et al., 2011).

Circ -4 also recommends a lower discount rate in the case of longer-term decision-
mak it includes intergenerational impacts, in which case "the agency might
con sensitivity analysis using a lower but positive discount rate, ranging from 1
perc 3 percent, in addition to calculating net benefits using discount rates of
3 pe nd 7 percent" (OIRA, 2011).

The aches thus far have been focused on financial markets (i.e., stocks and bonds).
Anc pproach to estimate a discount rate is to develop an implied social discount
rate time preference, risk/inequality aversion, and expected growth rate using the
Ran ule (NAS, 2017). The literature using this approach have estimates of the
imp ng-term social discount rate ranging from 1.4 % to 6.0 % depending on the
stuc S, 2017).

Agg d average discount rates discussed above range from -0.5 % to 7.0 %.
Hov a [PV][2] user may have a different personal real discount rate than the
esti or prescribed social or economy-wide discount rates because personal
pref s can vary significantly from person to person. Studies have found some real
pers iscount rates can vary from 0 % to 30 % with many finding average personal
disc ites higher than 7.0 % depending on the specific demographics, magnitude of
the ff values, and topic and approach in the study (Alberini & Chiabai, 2007;
Can & Gerdes, 2002; Moore & Viscusi, 1990; Scharff & Viscusi, 2011; Warner &
Plee 01). Therefore, it is important for the users to consider the purpose of the
anal nd select an appropriate discount rate.

3.3. lation Rate

The t inflation rate is set based on the average inflation rate projected for the next 10 ỵ .3 %) published in the most recent Report of the President's Economic Adv Analytical Perspectives (CITE). As with the discount rate, a user should con hether this inflation rate is appropriate for their expectations. Since 2010, the infl ite has varied from year to year between 0 % and 3 %. However, short-term infl ites in 2021 have risen significantly and there is uncertainty as to whether thes ion rates will subside or continue in the near future. A common data source for inflation rates is the Consumer Price Indices (CPI), which can be obtained here ://www.bls.gov/regions/subjects/consumer-price-indexes.htm.

3.4 nomic Data

Mo e economic data required to complete the economic analysis are available fror olar installer and/or the electricity provider, whether it's the costs associated witl lar installation, electricity consumption and costs, or available financial ince In cases where the required information is not available from the solar inst electricity provider, the user can use the following sources:

- d costs for solar photovoltaic systems can be obtained from several different s
  - 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
- ind state financial incentives are available from Database of State Incentives newables & Efficiency (DSIRE) USA: https://www.dsireusa.org/.
- REC markets and credit prices can be found at SRECTrade: www.srectrade.com/.
- contract options are available from SREC aggregators such as SolSystems: www.solsystems.com/srec-services/state-srec-markets/).
- verage electricity price can be obtained from the EIA: www.eia.gov/electricity/data.php#revenue under "Sales (consumption), e, prices & customers" > "Average retail price of electricity to ultimate ers."

Def ta for the "Advanced" options are as follows:

- escalation rates are defaulted to values from Lavappa and Kneifel (2021) based on energy price projections at the Census Region level from the EIA.
- l maintenance costs are defaulted to $0.03/W based on values from Webb, l, and O'Fallon (2020), which represent annual equipment check-up and g.
- anel lifetime is defaulted to 25 years (CITE)

- r 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
- ement costs for string inverters is defaulted to $0.18 (Webb et al., 2020); only r string inverters
- efficiency degradation rate is defaulted to 0.5 % (J Kneifel, Webb, & , 2016); solar panel equipment specification sheets typically provide ed degradation rates (often available from solar installer)

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

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

3.5 rnality Costs

Ext es are an impact that affects other parties that are not reflected in the cost of a pro this case, it is an impact that is not included in the economic analysis. An ext can be included in the economic analysis if those externalities can be mo . $[PV]^2$ does not include any externalities in the economic analysis but does pro externality cost for GWP as a separate reported economic measure. GWP is also ed using LCIA measures, as are other impact categories that are more diff r possibly impossible, to monetize.

3.5. cial Cost of Carbon

[PV ently uses a fixed price for the social cost of carbon, $51/metric ton, which is bas missions in 2020 assuming a 3 % discount rate (United States Government, 202 GHG emissions measured by the GWP impact category (CO_2e emissions) are incl egardless of whether the emissions are embodied in the solar photovoltaic syst he grid-based electricity. However, the SCC has been projected to rise over tim e versions of $[PV]^2$ could introduce time varying prices if deemed beneficial to u well as the ability for the user to customize the SCC value(s).

Uni tes Government (2021) provides distributions of SCC estimates (2020 US doll suming different discount rates: 5 %, 3 %, and 2.5 %. Table 3 -7 shows the ave C values for each discount rate in 5-year increments. A 4th value, the 95th per value for the 3 % discount rate case is an example of a high SCC scenario. The te distributions have a left-skewed distribution with long right tails. Please see States Government (2021) for more detailed information on these dist s.

Tab   Social Cost of Carbon Estimates

SC	letric Ton (2020 US dollars)			
Year	Average Price			95th Pct
	%	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. sts of Other Environmental Impact Categories

The of other environmental impact categories are not currently included in [PV][2], but be included in future versions.

4 ronmental Performance Evaluation

For vith a background in life cycle assessment (LCA), it is beneficial to provide tech etails on the LCA data and modeling methodology. Although the authors hav pted to provide the content as straightforward as possible, this chapter may not ly understandable for some users.

The for the solar photovoltaic equipment and grid-based electricity consumption hav conducted in accordance with the requirements of the ISO 14040 and 14044 stan or LCA (International Organization for Standardization (ISO), 2006a, 200 ıvironmental LCA is a "cradle-to-grave," systems approach for measuring env ntal performance. The approach is based on the logic that all stages in the life of a ct generate environmental impacts and must therefore be analyzed, including raw als acquisition, product manufacture, transportation, installation, operation and nance, and ultimately recycling and waste management. An analysis that excl ny of these stages – without explicit rationale for doing so – is limited bec ignores the full range of upstream and downstream impacts of stage-specific pro

The th of LCA is its comprehensive, multi-dimensional scope. Some green pro ims and strategies are based on a single life cycle stage or a single env ntal impact. A product may be claimed to be green simply because it has recy ontent or accused of not being green because it emits volatile organic com s (VOCs) during its installation and use. These single-attribute claims may be mis because they ignore the possibility that other life cycle stages, or other env ntal impacts, may yield offsetting effects. For example, a product with recy ontent may have a high embodied fuel content, leading to fossil fuel depletion, GW acid rain impacts during the raw materials acquisition, manufacturing, and tran ion life cycle stages. LCA thus broadens the environmental discussion by acc for potential shifts of environmental problems from one life cycle stage to ano one environmental medium (land, air, water) to another. The benefit of the LC bach is in implementing a trade-off analysis to assess where in the life cycle ove bacts may be reduced, rather than limiting the scope to a shift of impact.

The l LCA methodology involves four steps (International Organization for Sta ation (ISO), 2006a, 2006b).

1. nd scope definition
2. ory analysis
3. assessment
4. etation

The nd scope definition step outlines the purpose of the study and its breadth and dep inventory analysis step identifies and quantifies the environmental inputs and out ociated with a building product over its entire life cycle. The quantification and ;ation of results is called the LCI, which includes elementary flow inputs (i.e., reso rom the earth, such as water, fossil fuels, minerals). Elementary flow outputs incl eases to air, land, and water. The LCI output is large, and it is difficult to assi ning to its individual elements. Nonetheless, we are interested in the LCI flov sequences, or how they may potentially impact the environment and human hea this determination is done in the impact assessment step. The impact asse step characterizes the flows in the LCI results in relation to a set of env ntal impacts. For example, the impact assessment relates carbon dioxide (CC other greenhouse gas (GHG) emissions (e.g., methane), to GWP (an impact). Fina interpretation step examines the results in accordance with the goals of the LC/ .

4.1 ironmental LCA Goal and Scope Definition

The f [PV][2] LCAs is to generate environmental impacts for owning and operating resi solar photovoltaic systems in the United States. These impacts are combined witl mic analysis to help the homeowners make cost-effective, environmentally-pref olar investment decisions. The goal and scope definitions include defining the syst ndaries, cut-off criteria, the functional unit, and the data collection strategy.

4.1. stem Boundaries

Def e system boundaries involves identifying the unit processes to be included and the fe cycle stages that are included in each product LCA. A unit process is the "sm element considered in the LCI analysis for which input and output data are qua "[1] The manufacture of a product usually involves many unit processes (e.g., ethy roduction for input to the manufacture of the styrene-butadiene bonding agent use cco cement in cladding). Each unit process involves many inventory flows, som hich themselves involve other, subsidiary unit processes. The main unit pro equiring data collection are, at minimum, within the main life cycle stages defi the system boundaries. These are:

- aterials Production: production of the materials in the building products. ortation of materials to a manufacturing facility as well as production of ing materials are included in this stage.
- acturing: manufacturing operations to build the product.
- ortation to installation: Transportation of the finished, packaged product to the installation is generally done by truck or rail, as most of the products are ed in the United States. Some products are produced outside North America, s transportation (by ocean freighter) is accounted for in these situations.
- ation, where data are available.
- se phase emissions for solar photovoltaic system products is captured by the ity production based on the impacts of grid-based electricity reduction.
- Life: fate of the product at end of its life.

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[1] Se f International Organization for Standardization (ISO) (2006b).

4.1. t-off criteria

ISO · requires a cut-off criterion to be defined for the selection of materials and proc o be included in the life cycle stages above. Several criteria are used in LCA prac decide which inputs are to be studied, including mass, energy and env ntal relevance. For the product LCAs, the mass criterion was always applied, and ff goal of 95% has been defined. Mass was used since masses of materials are mos fically defined and quantifying mass throughout the systems – including what is n ided - is most straightforward. Energy and environmental relevance are more diff use since there is less certainty with these parameters to be able to claim that the s been met. For example, if energy to produce certain inputs in a system has unc values, then the basis with which to calculate total energy and missing energy bec ncertain. Detailed information on the inputs of a product's system are gathered, and effort is made to include the production data for all parts and materials. The proc apters highlight where specific data are missing.

4.1. clusion from System Boundaries

Hur ivities are excluded from the system boundaries of the LCAs of these building proc Humans are involved in all aspects of the life of these products (factory wor iving to and from work, generating waste at the facility; transporters; users of the ts…). These activities could be included in the system boundaries, but human acti re generally excluded from an LCA since it can be argued that these same peo ıld still contribute to environmental factors whether or not they are con g to the production or use of these products. Capital equipment is excluded exc ıetimes, when it is included as part of a background data set.

4.1. nctional Unit

To t an ISO-compliant LCA, all flows within the system boundaries must be norı l to a unit summarizing the function of the system, enabling the comparison of proc r systems on an equivalent basis. The functional unit is thus defined so that the proc ompared may be true substitutes for one another. The functional unit provides the reference point to which all inventory flows are scaled. The functional unit for the ıodeling of a solar photovoltaic system is the service life of the system. The fun unit for the LCA modeling of grid-based electricity is one unit of electricity con on-site as the building. In [PV][2], the functional unit is the installation and ope (and replacement if necessary) of the solar photovoltaic system over the sele ıdy period.

4.1. ta Requirements

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

- entativeness – the qualitative assessment of degree to which the data set ; the true population of interest. Representativeness includes geography (i.e., vered), temporal data (i.e., the age of data and length of time over which data be collected), and technological coverage (i.e., the technology mix);
- tency – the qualitative assessment of how uniformly the study methodology is l to the various components of the analysis;
- lucibility – the qualitative assessment of the extent to which information about thodology and data values allows an independent practitioner to reproduce the reported in the study;
- on – the measure of the variability of the data values for each data category sed;
- eteness – the percentage of locations reporting primary data from the potential r in existence for each data category in a unit process.

The lescribed in in the Data Quality Evaluation section.

4.2 ntory Analysis

Inv analysis entails quantifying the inputs and outputs for the unit processes wi product system. One of the primary tasks is data collection that ensures the pr ystem evaluated is representative and appropriately addresses the cut-off cri ata and data quality requirements, and other scoping factors. Data are co for each defined unit process. As shown in Figure 4 -14, to produce a given pr r intermediate product, inputs collected include energy, fuels, net water use, an materials, and product components/materials. Outputs may include direct em ; to air and water, and waste categories.

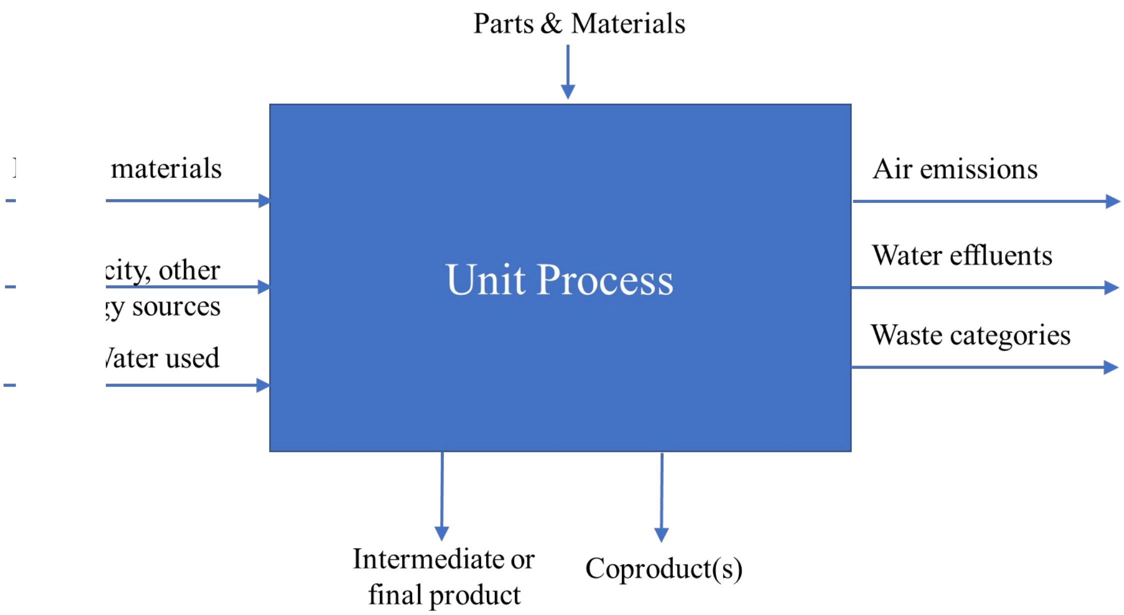

Figure 4-14 BEES Inventory Data Categories

Nur approaches may be used to collect inventory data for LCAs. These range from (EP 3):

- ›rocess- and facility-specific: collect data from a process within a given y that are not combined in any way
- ›osite: collect data from the same process combined across locations
- ›gated: collect data combining more than one process
- try-average: collect data derived from a representative sample of locations ›ed to statistically describe the typical process across technologies
- iptive: collect data whose representation may be unknown, but which are atively descriptive of a process

For ar photovoltaic system, U.S.-average data and results, generic product data are prin :ollected using the industry-average approach. It is NIST's goal to strive for pro ta that represents the closest approximations available of the impacts and attri ıssociated with each product. Some of the products are built using detailed LC :ionnaires and/or shorter surveys sent to industry experts, while others are built usir ished LCA reports. In most cases, any assumptions regarding the associated unit ›ses are verified through experts in the respective industries to assure the data hav appropriately represented. Today, many industry average and company spe oducts have already-published EPDs, which are based on externally verified LC products in [PV][2] that have undergone the EPD process, much, if not all, of the t data come from the EPDs' supporting LCAs, with the approval of the EPD owı

Dat take care of background data sets, which are the supporting data for the pro lefined unit processes. Background data can include materials, energy and fuel inpu l transportation. Where manufacturers do not have control over data on their pro uch as whether their product is recycled or landfilled at end of life, the LCA pra r uses industry-backed data on the typical practice.

4.3 Cycle Impact Assessment

4.3. :thodology

Env :ntal impacts from building construction and use derive from the inputs and out :curring throughout production supply chains. The LCIA step of LCA quantifies the al contribution of these inventory items to a range of environmental impacts. The ıch preferred by most LCA practitioners and scientists today involves a two-step ›s:

ıssification of inventory flows that contribute to specific environmental ›acts. For example, greenhouse gases such as carbon dioxide, methane, and ›ous oxide are classified as contributing to climate change.

ıracterization of the potential contribution of each classified inventory flow to corresponding environmental impact. This results in a set of indices, one for h impact, which is obtained by weighting each classified inventory flow by its ative contribution to the impact. For instance, the Global Warming Potential WP) index is derived by expressing each greenhouse gas in terms of its iivalent amount of carbon dioxide heat trapping potential.

The wo general applications of this LCIA approach. The midpoint-level analysis qua environmental burdens along the cause-effect chain. There are many mid-point cate which make straightforward interpretation challenging, but mid-point calc s are generally more scientifically defensible. The endpoint-level analysis take nid-point calculations further and attempts to measure the ultimate damage that eacl onmental input and output in the inventory has along the cause-effect chain. End ategories, such as damage to human health, ecosystems, and resource avai /, make interpretation easier, but this approach is criticized for the numerous assu ns, value judgments, and gaps in coverage of the underlying damage models.

The int-level analysis does not offer the same degree of relevance for all the impact cate For global and regional effects (e.g., climate change and acidification) the met ovides an accurate description of the potential impact. For impacts dependent upo conditions (e.g., smog), it may result in an oversimplification of the actual imp cause the indices are not tailored to localities. Note that some impact asse ts apply a mix of midpoint and endpoint approaches. It should be emphasized that results are relative expressions and do not predict impacts on category end the exceeding of thresholds, safety margins or risks.

PV[2] ne midpoint-level analysis to translate its environmental inputs and outputs into a m ble set of science-based measurements across environmental impacts. The LCI nodology uses U.S. Environmental Protection Agency's (EPA) Tool for the Red and Assessment of Chemical and other environmental Impacts (TRACI) vers . set of state-of-the-art, peer-reviewed U.S. life-cycle impact assessment met Bare, 2011). Additionally, Total Primary Energy Consumption is used to prov e-cycle primary energy associated with the building. Together these methods are develop performance metrics indicating the degree to which construction and use ilding contributes to each environmental impact. What follows are brief desc ns of the impact categories.

4.3. obal Warming Potential (CO_2e)

The absorbs radiation from the Sun, mainly at the surface. This energy is then redi ed by the atmosphere and ocean and re-radiated to space at longer wavelengths. Gre e gases in the atmosphere, principally water vapor, but also carbon dioxide, met hlorofluorocarbons, and ozone, absorb some of the thermal radiation. The abso nergy is re-radiated in all directions, downwards as well as upwards, such that the on that is eventually lost to space is from higher, colder levels in the atm e. The result is that the surface loses less heat to space than it would in the abse the greenhouse gases and consequently stays warmer than it would be othe This phenomenon, which acts like a 'blanket' around the Earth, is known as the ouse effect.

The ıouse effect is a natural phenomenon. The environmental issue is the change in the ouse effect due to emissions (an increase in the effect) and absorptions (a decı ı the effect) attributable to humans. A general increase in temperature can alter atm ic and oceanic temperatures, which can potentially lead to alteration of natural circ s and weather patterns. A rise in sea level is also predicted from an increase in tem e due to thermal expansion of the oceans and the melting of polar ice sheets.

4.3. tal Primary Energy Consumption and Related Energy Categories (MJ)

Tot ary energy consumption comprises all energy associated with a product syst cluding energy used as fuel for product manufacturing as well as upstream and dow n processes (raw material production, transportation, operational use, etc.). Prir ıergy also includes the embodied energy of a product, such as hydrocarbons emt in plastics. Total primary energy is broken down into **renewable** and **non-ren** **energy** and **fossil fuel energy**. Non-renewable energy accounts for the energy con ım fossil fuels and other non-renewable resources used such as uranium for nuc wer. Hydropower, wind, geothermal, and biomass energy are classified as rene Fossil fuel energy quantifies the energy coming only from the fossil fuels incl petroleum, natural gas, and coal. All these categories are reported in meg s (MJ).

4.3. idification Potential (SO_2e)

Aci compounds may, in a gaseous state, either dissolve in water or fix on solid part These compounds reach ecosystems through dissolution in rain or wet dep and can affect trees, soil, buildings, animals, and humans. The two compounds prin involved in acidification are sulfur and nitrogen compounds, with their prin uman source being fossil fuel and biomass combustion. Other compounds rele human sources, such as hydrogen chloride and ammonia, also contribute to acic ın.

4.3. trophication Potential (Ne)

Eut ıtion is the addition of mineral nutrients to the soil or water. In both media, the add large quantities of mineral nutrients, such as nitrogen and phosphorous, resı generally undesirable shifts in the number of species in ecosystems and a redı n ecological diversity. In water, it tends to increase algae growth, which can leac ck of oxygen and subsequent death of species like fish.

4.3. ıog Formation (O_3)

Smı ıs under certain climatic conditions when air emissions (e.g., nitrous oxides (NC atile organic compounds (VOCs)) from industry and transportation are trapped at g evel where they react with sunlight. Smog leads to harmful impacts on human heal vegetation.

4.3. one Depletion (CFC-11e)

Ozc letion is the thinning of the stratospheric ozone layer, allows more harmful shor radiation to reach the Earth's surface, potentially causing undesirable changes in e ms, agricultural productivity, skin cancer rates, and eye cataracts, among other issu

4.3. spiratory Effects (PM2.5e)

Res y effects look at particulate matter and air emissions generated by use of fuels for icturing and transportation and materials handling, that when inhaled, may resu ealth issues such as asthma and other respiratory illnesses. This impact category is re in kg PM2.5-eq (particulate matter of size less than or equal to 2.5 mic rs).

4.4 r Photovoltaics

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

Pre developed for BIRDS NEST, models were developed that specify four diff olar panels and their racking hardware; three different inverter systems; and an elec monitoring device. Each system is modeled based on a functional unit of one wat The individual components have been calculated on a per-kilowatt-potential (kW is, as this can be translated to any sized system and is not dependent on loca

The owner is unlikely to know where the manufacturing facility of the solar panels is lc Therefore, the model for [PV][2] currently hard-codes the source country for the sola s to U.S.-based production. An option could be included in a future version to pro eater granularity. This could be accomplished by adding a database of solar pan d and product lines that includes their manufacturing facility locations.

Fig -15 presents the photovoltaic system boundaries.

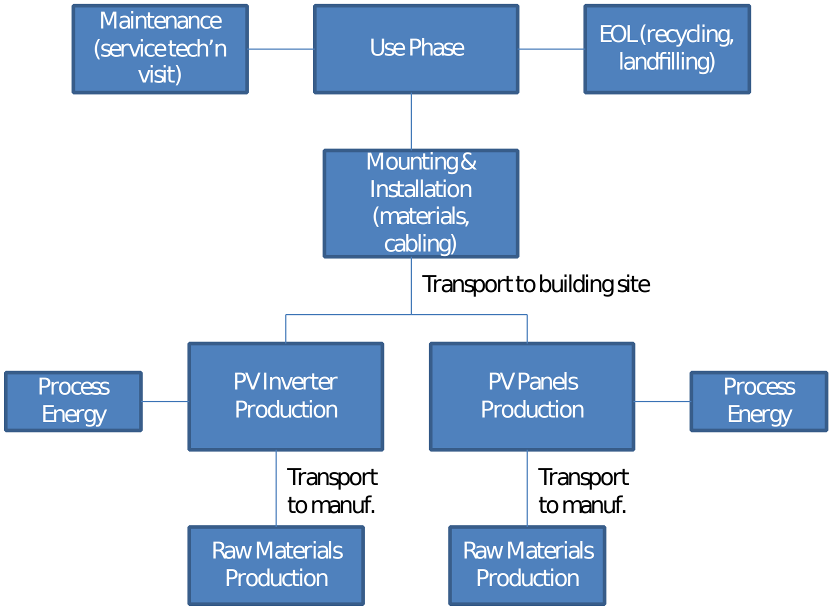

Figure 4-15 Solar Photovolatic System Boundaries

4.4. stream Materials Production through Manufacturing

Ma rer-specific data were not available, so publicly available sources of data were use ifically, the crystalline silicon solar panel, inverter, and associated cabling are bas esearch by Mariska De Wild and Erik Alsema (Fthenakis, 2011), which were com y ecoinvent to build comprehensive inventories. (Jungbluth, 2007)

4.4. otovoltaic Panels and Racking System

Pho aic panels. The photovoltaic panels include:

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

The solar panel LCI data in ecoinvent were provided by industry yet are not mar rer specific. They can be considered a reliable representation of crystalline silic dule production technology for 2005/2006 and are based on Western Europe pro . Due to the detailed bill of materials, the data are not presented in this report. Ho Figure 4 -16 is provided to provide clarity around the processes involved in the tion of these solar panel using a monocrystalline solar panel as an example (Ft , 2011).

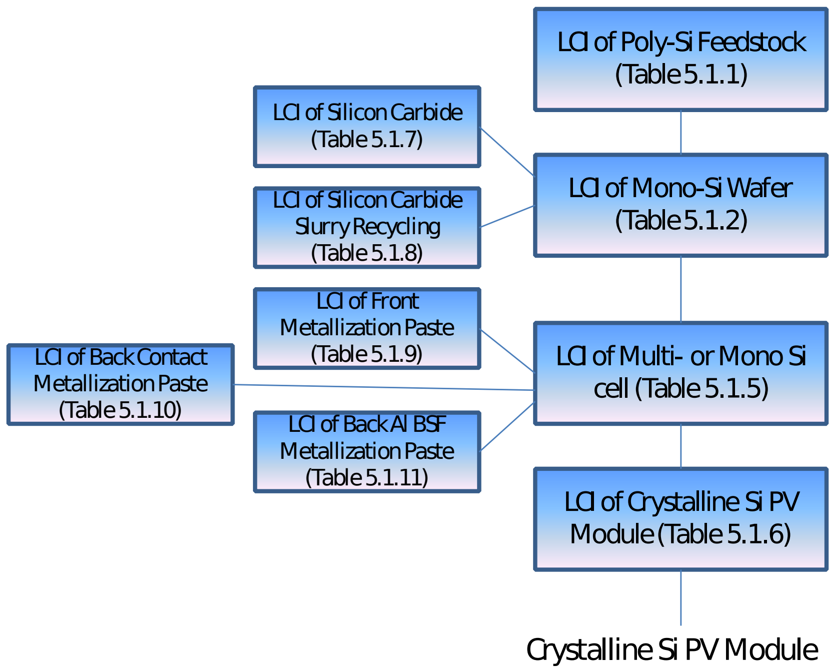

Figure 4-16 PV Module Production Data Sets

To l olar panel models that are representative of products on the market today, a web was performed to understand specifications for more current products on the mar en the ecoinvent datasets that were most closely aligned with the products on the were adjusted to the current products' general specifications, as shown in Tab 3. The last item in the table represents the racking or mounting hardware.

Tal 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)
Mc alline Panel (>2 1	1.63 (0.15)	280	18 (39.7)	0.0058 (5.6 E-4)	0.064 (0.14)
vent data set and value used →	Photovoltaic panel, single-Si wafer production ~ 0.006 m^2 (5.6 E-4 ft2)				
Mc alline Panel (15 ote 2	1.86 (0.18)	415	21.1 (46.5)	0.0045 (4.7 E-4)	0.051 (0.11)
vent data set and value used →	Photovoltaic panel, single-Si wafer production ~ 0.005 m^2 (4.7 E-4 ft2)				
Pol lline Panel (13- 16 1a note 3	1.63 (0.15)	250	19.5 (43.0)	0.0065 (6.6 E-4)	0.078 (0.17)
vent 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)				
Pol lline Panel (13- 16 note 3	1.63 (0.15)	250	19.5 (43.0)	0.0065 (6.6 E-4)	0.078 (0.17)
vent 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)				
Ra Mounting sys	Photovoltaic mounting system, for slanted-roof installation (RoW)| production				

No duct data based on Solar PV Module HON-M60B, found at: http enfsolar.com/Product/pdf/Crystalline/5b724fc42aece.pdf? _ga 271110.1151162136.1565887874-1576003210.1565887869.
No duct data based on SunPower 400–425 W Residential AC Module, found at: https://es- me .s3.amazonaws.com/media/components/panels/spec-sheets/SunPower_A-Series.pdf
No duct data based on TrinaSolar TSM-PC/PA05A, found at: http v.energymatters.com.au/images/trina-solar/trina-pc05a-250w.pdf

Sin lata are based on Western Europe, wherever possible, data representing North Am production were used to adjust the data to be more appropriate for North Am conditions; U.S. LCI database and other North American data sets were used to repl ne of the process energy, transportation, and upstream materials data sets (e.g., fran aterials, auxiliary materials, etc.). For the polycrystalline panel produced in Chi China electricity grid was applied. Detailed information is provided in the tabl renced in Figure 4 -16 and/or Jungbluth (2007).

Rac ystem. For the racking system, the industry weighted-average materials and pro n Fthenakis (2011) Table 5.4.2 were used. The data are provided for 1 m^2 (10. f a mounted PV module on a slanted roof. This was normalized to the Wp valu responding with the panel areas listed in Table 4 -8. Data for electrical cabling for : interconnection and AC-interface is provided by Fthenakis (2011) Table 5.5. d is provide in Table 4 -9.

Tal Solar Panel Mounting Materials and Cabling

Mc Material	kg per m^2	lb per ft^2	Notes
Alı	2.84	0.58	plus section bar rolling
Co: board	0.013	0.003	
Pol ıe	0.0013	0.0003	
Pol	0.006	0.0013	
Lo d steel	1.50	0.31	plus steel sheet rolling
Ca aterial			
Co	0.10	0.021	2.2 m DC cable and 0.1 m AC cable
Th ıtic elastomer	0.06	0.013	

4.4. otovoltaic Inverters and Electronic Monitoring System

Pho ıic Inverters. The inverters used in [PV]^2 include a string inverter, a mic ter, and a string inverter with an optimizer. The string inverter is one of the mos non types of inverters used in residential applications. A string inverter is con to a "string" of solar panels, converting power from DC to AC for all the pan croinverters are smaller-sized and attach to each panel instead of one central inve Vhile micro-inverters are more expensive to install, they are useful when part of a pa n the shade or if the roof is too small to have a string of panels. When an opti s installed with an inverter, the optimizer improves overall system perf ce and can draw from individual panels to maintain output (i.e., when part of the is shaded).

Inve ı ecoinvent, described in (Jungbluth, 2007), were normalized to a Wp output base ıeir rated capacity in the data sets. Table 4 -10 presents the data sets and the qua each unit applied per Wp.

Tal) PV Inverters Data Sets Used

	ecoinvent Data Set & Quantity per Wp	Notes
Str ter.	Inverter, 2.5kW (RoW)| production ~ 0.0004 unit	
Inv 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
Mi ter	Inverter, 0.5kW (Dorer & Weber)| production ~ 0.002 unit	

Mat ıre modeled as transported to the manufacturing plant via diesel truck an assu ɾerage distance of 805 km (500 mi). Transportation data come from the U.S. LCI ıse.

Sol ıitoring System. Solar power monitoring systems enable homeowners to mon lar electricity production and/or the home's energy usage. Monitors are often sma ronic devices; the data set used as a proxy for a monitor on the market is the eco LCD module. Monitors are small and efficient; the monitor in [PV][2] is mod fter a 9.0 g (0.02 lb) device and is assumed to work for a 3000 Wp system.[2]

4.4. ansportation to the Building Site through End of Life

Tra tion of the solar panels and other components in this system an assumed ave 2414 km (1500 mi) by heavy-duty diesel fuel-powered truck. The exception to this ransport from China, in which ocean freighter from Asia to the U.S. West Coa lded to the model.

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

Ove PV panels can degrade at a rate of one percent per year. The Solar Energy Indu Association (SEIA) states that the lifespan of solar panels can last from 20 to 30 y SEIA, 2015). [PV][2] models the monocrystalline panels with a 30-year lifetime whi olycrystalline are assumed to have a 20-year lifetime. SEIA (2015) states a life 10 years for the inverter. The racking system has a lifetime of 60 years or bey ıe monitoring system is re-purchased after 10 years.

At e ife, materials from solar panels are assumed to be sent for recycling for mat covery. The recycling process for silicon-based modules can be described as foll For silicon-based modules, aluminum frames and junction boxes are dismantled mar .. The module is subsequently crushed and its several components are sep allowing recovering up to 80% of the panel."[3] An LCA screening study by Fra ꞉ (2012) demonstrated that valuable materials like aluminum frames, copper, and ullet can be successfully recovered at a flat glass recycling facility. At the time of t ing, in the U.S., recycling of PV panels is not mandated. However, it is exp ıat as recycling of PV panels becomes a streamlined operation and as PV

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

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

pan in to exceed their useful lives, recycling will be industry standard practice. Not ·V panels are required to be recycled in the EU today.[4]

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

4.5 rational Electricity

Ope ıl electricity production inventory data are applied to a building's consumption and :tion of electricity to convert site flows to source flows, which are customized to a .c location based on the user provided location (specifically ZIP code) to calc ıe operational electricity LCA results.

4.5. mporal Scope

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

DO tional Energy Technology Laboratory (NETL) developed a reproduceable mod generating these attributional LCA and LCIA results using data profiles for elec production consumed in the United States. The life cycle data profiles are doc d in a forthcoming NETL-published report and will be available for download in a :iated spreadsheet. The primary data source details for each fuel type are listed in T 4 -11.

Tal l Operational Energy LCA Data Sources

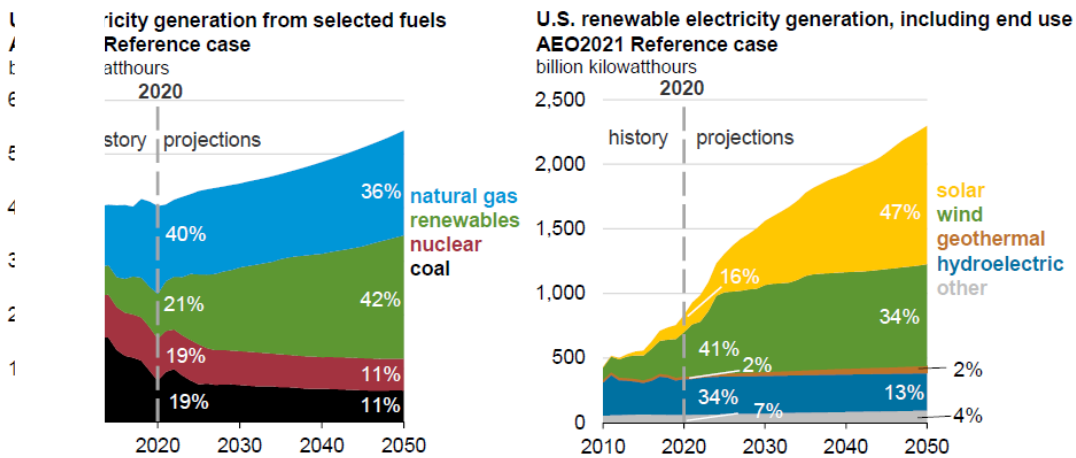
Fu		Regionalization	Data Source	Developer	Data Year
Ele		Balancing Authority	U.S. Electricity Baseline Model	Federal LCA Common / NETL Grid Mix Explorer	2018

The :wo options use the attributional model results and EIA Annual Energy Out)21 (AEO2021) projections to develop generation based LCAs to allow for cha he projected fuel mixes over time. Electricity will realize significant changes in the ımental impacts associated with its generation and consumption because the fuel ıs been changing and will continue to change over the next few decades. The "Pr ı – Baseline" option uses the AEO2021 Reference case as the basis for the

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

assu hange in electricity fuel mix out to 2050 while the “Projection – High Ren ” option uses the AEO2021 Low Renewable Cost case.

Figu -17 is the figure on page 1 of EIA (2021), and shows that the AEO2021 Ref case projects electricity generation from renewables will double its share of tota ation from 21 % in 2020 to 42 % in 2050. The Low Renewable Cost case wou l to an even higher renewable share of 57 % by 2050. These significant chan the fuel mix will lead to changes in the environmental impacts of a unit of elec consumption. For example, EIA projects that from 2020 to 2050, the total ann oon emissions from the electric power sector will be reduced by 14 % while tota icity sales will increase by 30 % over the same timeframe.



ure 4-17 Electricity Generation by Fuel – AEO2021 Reference Case

The onal average projections express the significant changes that are expected to occu e U.S. electric grid over the next 30 years under current regulatory and econ conditions. The fuel mix projections across balancing authorities vary sign ly both in terms of the initial state of the fuel mix and the expected change in the x over time. By controlling for these differences, BIRDS NEST can provide mor ate LCA data projections for electricity for a given building location.

The wo limitations that should be acknowledged for the current electricity LCA dev nt process. First, the electricity generation fuel mix in a balancing authority can significantly from season to season, day to day, and even hour to hour. It wou echnically feasible to identify the marginal generating unit for each hour of ever and develop an LCA for each of these units. However, a homeowner will not hav s to the necessary data. A solar installer will provide estimated annual proc (typically only for the initial year of operation) of the solar photovoltaic syst iking it impossible to identify the marginal generating unit for sub-annual time peri econd, the incorporation of battery storage related LCA data is not currently incl future projection cases. The implications of battery storage are difficult to moc ause of the fast-moving technological advances and the quickly shifting econ of battery storage. Future updates to the operational electricity data could con… ıcluding sub-annual variation in fuel mixes as well as incorporate battery stor… ›jections if it is determined to be beneficial.

4.5. …ographic Scope

The… aphical scope of the operational electricity LCA data are at the U.S ZIP code leve… ıe continental United States. Each ZIP code is mapped to appropriately defined EIA… ›t regions (i.e., Balancing Authority). Note that the mapping of ZIP code to thes… ıns requires subjective assignment in geographical areas where the ZIP code app… more than one market region. The nearest neighbor approach aligned to the geo… :al resolution of the underlying data for each energy commodity is used in thes… tions.

The… ;. balancing authorities are used as the market regions for electricity. Figure 4 -18… the North American Electric Reliability Corporation (NERC) regions and the bala… authorities within those NERC regions developed by the EIA (EIA, 2016). Det… ıformation is available at the balancing authority level on electricity generation, con… on, and inter-balancing authority trading, providing a more accurate estimate of the… ɛ fuel mix for a given location than the commonly used NERC region level data… ıot realistic to use further disaggregated data because a unit of electricity can… :racked through the balancing authority grid. As can be seen in Figure 4 -18, bala… authorities do not always align with state and/or county borders, making it inap… ate to map to those boundaries. Although the same issues may arise to a lesser exte… ı the use of ZIP codes, the level of precision is much higher and the potential geo… :al area that could be mismatched is minimized.

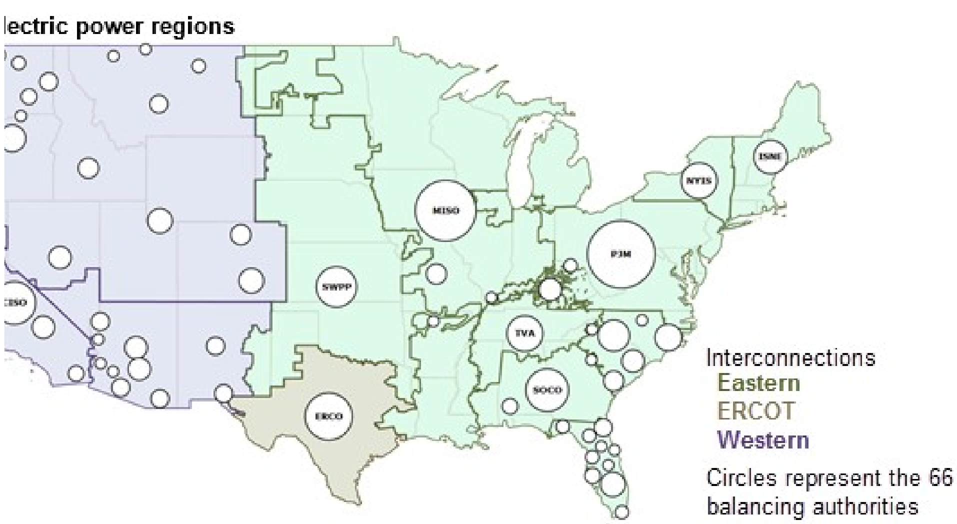


Figure 4-18 NERC Regions and Balancing Authorities

4.5. …A and LCIA Methodology

The… levelopment is cradle-to-grave for on-site electricity consumption. All known air… ter emissions contributing greater than 1 % to each impact assessment met gy. The scope of emissions data is limited to emission data that industry repo he U.S. government; specifically, the EIA and EPA. Note that discussions hav n to expand the U.S. Electricity Baseline to include Canada and Mexico to pro North American Electricity Baseline to improve consistency of background ope l energy LCA data. The operational energy LCA data will be updated annually and orate the most up-to-date data available as well as any improvements and/or exp s of the Electricity Baseline model.

The methodology is consistent with the solar photovoltaic system LCA. The data incl l the impact categories as described in Section 4.3 as well as three other TR impact categories (Carcinogenic Potential, Non-carcinogenic Potential, Eco y Potential). These additional impact categories are excluded from any further disc in this document because they are not included in PV^2.

GW ntial is provided using both the TRACI 2.1 life cycle impact assessment met gy and International Panel on Climate Change (IPCC) Fifth Assessment Rep R5) GWP values with climate feedback. The option was designed into the pro allow users to select which option best fits their LCA modeling requirements and ferences. PV^2 uses the TRACI 2.1 methodology and will remain consistent witl nethodology moving forward. Any updates to TRACI 2.1 will be incorporated into derlying data sources. As with the solar photovoltaic system LCA data, Total Prin nergy Consumption is based on the ecoinvent methodology as described in Fris ht (2007) that uses Cumulative Energy Demand (CED).

Tot ating electricity-related LCIA ($TLCIA_{E,i}$) for each environmental impact cate) over study period "T" for a building are estimated using the following forr here EC_t is electricity consumption in year t, EP_t is electricity production in yea $LCIA_{E,i,t}$ is the electricity LCIA for impact category i in year t:

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

LCI constant over time for the Benchmark option and variable for the two proj options. On-site electricity production from solar photovoltaics is assumed to offs equivalent consumption-related emissions. The solar photovoltaic production is assu degrade at an annual rate of 0.5 % ($EP_{t-1} = EP_t * (1 - 0.005)$) while electricity and l gas consumption is assumed constant ($EC_1 = EC_2 = \ldots = EC_T$ and GC $= \ldots = GC_T$).

5 vare Development and Design

For nterested in the details of the software design, this chapter discusses the dev nt tools used to create both the front-end web application and the back-end eco calculation engine. Note that some of the content will not be easily understood by s sers.

[PV web application that enables a user to evaluate the economic (through life cycle cos is) and environmental (through life cycle assessment) performance installing a roo ar photovoltaic system on a house using quotes from a solar installer and elec l information as described in previous sections of this report. Comparisons of life osts and environmental impacts for installing a solar photovoltaic system vers tinued purchase of grid-based electricity from the electricity provider can be eva using the data visualization features in the application. Technologies were sele r this project based on their utility in developing this comprehensive system. A sum of each technology is described below.

5.1]^2 Application

Sev b technologies were used in the creation of the [PV]^2 user interface. Hypertext Ma nguage (HTML) is the primary language used for displaying web content. Cas Style Sheet (CSS) is the definition file used by web pages for formatting. Jav is a light-weight scripting language used to programmatically manipulate the inp ut or display of a web page. TypeScript is an open-source language that builds on J ipt by providing a way to describe the shape of an object, providing better doc tion, and allowing TypeScript to validate that the code is working correctly. Wri pes can be optional in TypeScript, because type inference allows you to get a lot er without writing additional code. Other development tools may be considered in t e if new capabilities and features require them, such as adding more sig background data sources for auto-populating parameter values (e.g., electricity pric r installation costs, solar panel specifications).

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

The re is extensively beta tested and validated internally using multiple examples bef g released to ensure correct tool functionality, E3 input file creation, E3 out creation, and parsing of results.

5.2 nomic Evaluation Engine (E3) API

5.2. erview

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

Prev oftware development by AEO/EL Data, Software, and Technology (ELDST)
hav "one-off" tools that use similar (if not identical) back-end calculations. E3 has
beer ned as a generic API that can complete standards-based economic analysis
rega of topic area (e.g., buildings and infrastructure, community resilience,
sust manufacturing) or analysis type (e.g., LCCA, benefit-cost analysis (BCA),
prof imization), which will allow AEO/ELDST to focus its collective resources on
mai g and expanding the API functionality and capabilities to keep it up-to-date
and nt instead of duplicating maintenance efforts across a range of software tools.
Too leverage the API could be developed by AEO/ELDST (including transition of
exis ols), other EL or NIST researchers, federal and state government agencies,
acad , or the private sector (industry groups and individual companies) based on
thei sis needs at lower costs because much of the back-end development would
alre completed.

E3 l n developed with widely accepted and used open source tools throughout the
dev nt process, each of which is briefly discussed below. For additional details on
E3, see the E3 User Guide (forthcoming) and the E3 GitHub page
(htt hub.com/usnistgov/e3).

5.2. ogramming – Python, numPy, and pytest

Pyth n open source object-oriented, interpreted, and interactive programming
lang Python combines power with clear syntax, and has modules, classes,
exce , high-level dynamic data types, and dynamic typing. There are interfaces to
man em calls and libraries, as well as to various windowing systems. New built-in
mod e easily written in C or C++ (or other languages, depending on the chosen
imp ation). Python is also usable as an extension language for applications written
in o nguages that need easy-to-use scripting or automation interfaces. Python can be
used eb, graphical user interface (GUI), and software development, system
adm tion, and scientific and numeric analysis. NumPy is the fundamental package
for ic computing in Python. It is a Python library that provides a multidimensional

arra :t, various derived objects (such as masked arrays and matrices), and an assc of routines for fast operations on arrays, including mathematical, logical, sha ipulation, sorting, selecting, I/O, discrete Fourier transforms, basic linear alge sic statistical operations, random simulation and much more. Pytest is a mat l-featured Python testing tool. With pytest, common tasks require less code and adv asks can be achieved through a variety of time-saving commands and plugins. It w n run your existing tests out of the box including those written with Python’s unit odule.

5.2. amework – Django, Django REST Framework, and Django.test

Dja an open source, high-level Python web framework that encourages rapid dev nt and clean, pragmatic design. Built by experienced developers, it takes care of n the hassle of web development, allowing for focusing on writing the app witl eding to reinvent the wheel. Django includes dozens of extras you can use to han nmon web development tasks. Django takes care of user authentication, con ninistration, site maps, RDF Site Summary or Really Simple Syndication (RS ls, and many more tasks. Django helps developers avoid many common secu istakes, such as Structured Query Language (SQL) injection, cross-site scri cross-site request forgery and clickjacking. Its user authentication system pro secure way to manage user accounts and passwords. Django’s quick and flex ale can meet heavy traffic demands. Django can be used build content mar nt systems to social networks to scientific computing platforms.

Dja ST (representational state transfer) framework is a powerful and flexible tool building Web APIs. REST framework has several benefits, including the web bro API, authentication policies including packages for OAuth1a and OAuth2, seri n that supports both object-relational mapping (ORM) and non-ORM data sou mpletely customizable, and extensive documentation, and excellent con support.

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

- te GET and POST requests on a URL and observe the response.
- chain of redirects (if any) and check the URL and status code at each step.
- at a given request is rendered by a given Django template, with a template t that contains certain values.
- ango’s test client to establish that the correct template is being rendered and template is passed the correct context data.
- -browser frameworks like Selenium to test rendered HTML and the behavior of ages, namely JavaScript functionality.

5.2. ployment – PostgresSQL, Docker, AWS

Pos L is a powerful, open source, highly extensible object-relational database syst h a strong reputation for reliability, data integrity, robust feature set, exte ty, and the dedication of the open source community behind the software to con y deliver performant and innovative solutions. PostgreSQL runs on all major ope systems, has been ACID-compliant since 2001, and has powerful add-ons such as tl ılar PostGIS geospatial database extender.

Doc an open platform for developing, shipping, and running applications. Docker enal u to separate your applications from your infrastructure so you can deliver soft uickly. With Docker, you can manage your infrastructure in the same ways you mar ur applications. By taking advantage of Docker’s methodologies for shipping, testi d deploying code quickly, you can significantly reduce the delay between writ de and running it in production. Docker provides the ability to package and run an a ion in a loosely isolated environment called a container. The isolation and secu low you to run many containers simultaneously on a given host. Containers are ligh t and contain everything needed to run the application, so you do not need to rely at is currently installed on the host. You can easily share containers while you wor be sure that everyone you share with gets the same container that works in the sam

AW s information technology infrastructure services to businesses in the form of wet es (i.e., cloud computing). The E3 Docker Container is hosted on am AWS inst

6 tations and Future Development

The web application has several limitations related economic assumptions, LCA moc and LCIA methodology. Each will be summarized below. Additionally, pote ıture development of new capabilities and features in the application are disc

6.1 ıomic Assumptions

Nur assumptions required to complete the economic analysis are uncertain. Esti future costs accurately, particularly for costs more than a few years into the futu ifficult to impossible. Similarly, externality costs are difficult to estimate. The soci of carbon varies depending on the underlying assumptions (e.g., discount rate tionally, electricity production each year, how long a household will own a hon the service life of equipment can be estimated but are truly unknown. All a user ɔ is use the best information available at the time to make an optimal decision. It is mended that the user consider completing a sensitivity analysis of any assu ıs that they are concerned may change their decision.

6.2 ı and Uncertainty

It sh e borne in mind that LCA, like any other scientific or quantitative study, has limi and is a far from perfect tool for assessing exact environmental impacts and attri ıssociated with products and product systems. Uncertainty exists throughout all leve CA, from the background data to impact characterization to normalization fact ıantifying data uncertainty for the complete system becomes very challenging. Cur [PV]^2 does not include a formal uncertainty analysis but NIST is evaluating the ɔn of uncertainty analysis into future releases.

Des ɜse limitations, it should be emphasized that, the LCAs are built based on the best ıat were available at the time of the study using the same LCI database, utili e same background data sets (for example, for transportation data, energy proc , and materials production), and care is taken – using internal checks and bala ɜxternal peer review, and product-specific modeling rules – to ensure that proc ı the same category are built appropriately and objectively.

6.3 A

To ɜnvironmental performance, LCA models' inventory flows are converted to vari ɜal, regional, and global environmental impacts. While [PV]^2 incorporates stat ɜ-art LCIA methods, the science will continue to evolve, and methods in use toda continue to change and improve over time. Future versions will always inco ɜ improved methods as they become available and more universally accepted.

The ɔnmental Problems approach that [PV]^2 uses for impact assessment does not offe ıme degree of relevance for all environmental impacts. For global and regional effe ʒ., climate change and acidification) the method may result in an applicable desı ı of the potential impact. For impacts dependent upon local conditions (e.g., smc ɔarticulate matter) the method may result in an oversimplification of the actual imp cause the indices are not tailored to localities.

6.4 itional Features and Capabilities

The ɔtential to expand the capabilities and features in [PV]², including the addition of n fault data, methodology, system equipment, and results comparison options, con ɔn with other solar-related software, and sensitivity and uncertainty analysis.

Def ta options could be expanded for electricity prices by location, installed costs by l ı and technology, and solar panel specifications. Underlying databases would neeı developed and maintained to complete these matches, and reliable and up-t data sources would need to be identified. Examples of potential data sources cou ıde the following:

- city price data
  - OpenEI Utility Rate Database - https://openei.org/wiki/Utility_Rate_Database
- hotovoltaic 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
- anel specifications data
  - EnergySage - https://www.energysage.com/solar-panels/?product_line_status=current
  - NREL – System Advisor Model (SAM) - https://sam.nrel.gov/

Meı gy selection options could be expanded. Instead of defaulting to the linear dep ɔn approach, the remaining production value and/or the expected increase in resa e of the home could be included as an option. The LCIA data for future proj ; of the electricity grid could be included as options to account for the potential chaı the fuel mix over time. The user could be provided the option to include add environmental impact results in reporting, including those described in Section 4.3.

Sys ıipment options could be expanded to include battery storage options, which are ıng more common as the cost of batteries has dropped significantly in the last 5 yeaı costs of battery storage would be straight forward to include in [PV]². Hoν the economic benefits to a homeowner would require including low ɔility, high-impact events related to increased resilience (i.e., avoiding power outa

The t version of [PV]² allows the user to analyze a specific quoted solar pho ic system. However, each solar installer may provide different equipment opti ıt have different designs, prices, and performance. Additionally, most solar inst ɣill provide multiple system and size options depending on the homeowner's stat s (e.g., value versus quality, optimal production versus offsetting current con on) and constraints (e.g., budget, roof structure). A user could run analysis for eacl n and then manually compare the results using either the Portable Document For DF) reports or the results data in the CSV files. However, allowing such a com n from within the tool would be beneficial to help a homeowner quickly narr ir investment options.

Cor ation with other software tools to leverage their capabilities could be ben for users that are trying to determine if a solar photovoltaic system is a viable opti worth reaching out to get solar installation quotes. A user could use other tools that rrently available, such as EnergySage's Solar Calculator (htt w.energysage.com/solar/calculator), NREL's PVWatts (htt watts.nrel.gov/), or PVValue (https://www.pvvalue.com/). Some of the features in tl ols would be beneficial to incorporate into [PV]^2, either directly or through inte bility with those tools. Another tool that is not necessarily useful for hon rs, but could provide some excellent capabilities through interoperability is NR AM model (https://sam.nrel.gov/).

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

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