An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States

Brittany L. Smith, Ashok Sekar, Heather Mirletz, Garvin Heath, and Robert Margolis

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List of Acronyms

AB	avoided burden
ac	alternating current
BOS	balance of system
CED	cumulative energy demand
CO_2e	carbon dioxide equivalent
CPBT	carbon payback time
dc	direct current
DOE	U.S. Department of Energy
EOL	end of life
EPBT	energy payback time
EVA	ethylene vinyl acetate
g	gram
GHG	greenhouse gas
GW	gigawatt
GWP	global warming potential
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kWh	kilowatt-hour
kW_{dc}	kilowatt, direct current
LCA	life cycle assessment
MJ	megajoule
MW	megawatt
NETL	National Energy Technology Laboratory
NPCC	Northeast Power Coordinating Council
nr-CED	nonrenewable cumulative energy demand
NREL	National Renewable Energy Laboratory
oil-eq	oil equivalent
PERC	passivated emitter and rear cell
PV	photovoltaic(s)
PVF	polyvinyl fluoride
SETO	Solar Energy Technologies Office
Si	silicon
STC	standard test conditions
UPV	utility-scale photovoltaics
W	watt

Executive Summary

Goal and system description. Given the high deployment targets for solar photovoltaics (PV) to meet U.S. decarbonization goals, and the limited carbon budget remaining to limit global temperature rise, accurate accounting of PV system life cycle energy use and greenhouse gas emissions is needed. In the United States, most PV systems are large, utility-scale systems that use single-axis trackers and central inverters, which are not commonly examined in existing life cycle assessment (LCA) literature. In this study, we present a cradle-to-grave LCA of a typical silicon U.S. utility-scale PV (UPV) installation that is consistent with the utility system features documented in the National Renewable Energy Laboratory (NREL) annual PV system cost benchmark reports (Ramasamy et al. 2022). We analyze and present results for four main LCA metrics: cumulative energy demand (CED), greenhouse gas (GHG) emissions, energy payback time (EPBT), and carbon payback time (CPBT). CED represents the total energy consumed over the entire life cycle of the PV system, including energy needed to manufacture, install, and maintain the PV system, as well as energy needed for processing at the end of the PV system life when it is decommissioned. Similarly, the GHG emissions metric represents the carbon (and other greenhouse gases) emitted over the life of the PV system, including manufacturing, installation, maintenance, and end-of-life handling. EPBT is the time required for a PV system to generate the same amount of energy as needed for its entire life cycle (equivalent to CED). Similarly, CPBT is the time required for a PV system to offset the amount of carbon and GHGs emitted over its life cycle, by displacing more carbon-intensive electricity from the grid where it is installed.

Scenarios examined. In this LCA, we considered six primary manufacturing options: three based on an imported PV module supply chain (comparing low-carbon imports, high-carbon imports, and average imports), and three based on a potential domestic PV module supply chain (comparing low-carbon U.S. regions, high-carbon U.S. regions, and average U.S. regions). These manufacturing options were then paired with installation locations to create six main cases: low-carbon options were installed in Phoenix, Arizona, high-carbon options were installed in Seattle, Washington, and average options were installed in Fredonia, Kansas. The install locations were selected to represent a range of irradiance and grid mixes in the United States. The six main cases were chosen to span the range of EPBTs and CPBTs possible across the United States for each supply chain option (domestic vs. imported). For this reason, the six main cases pair low-carbon supply chains with the high irradiance location, while the high-carbon supply chains are paired with the low irradiance location and average-carbon supply chains are paired with the average irradiance location. For all six cases, a sensitivity analysis for end-of-life (EOL) handling was explored to capture current and future management options: landfilling, partial recycling, and hypothetical high-recovery recycling. For the purposes of this report, the benchmark system is defined as an installation in Fredonia, Kansas with an average imported supply chain and partial recycling.

Life cycle inventories. Inventories of material and energy inputs over the PV system life cycle were sourced from recent literature, current industry practices, and empirical data gathering to represent modern technology. We focused on the production of silica sand, silicon metal, polysilicon, single-crystal ingots, wafers, PV cells, modules, single-axis trackers, inverters, transformers, and other balance-of-system components, and on installation, maintenance, and end of life. Inventories were modeled using openLCA software (GreenDelta 2023) and the ecoinvent 3.9 life cycle inventory database (FitzGerald and Sonderegger 2022). Additionally, primary data were collected from a commercially available 2.7 MW_{ac} inverter to provide an updated inventory for utility-scale PV inverters. The empirical inverter inventory was collected from an installed preoperational inverter and built using material inputs and analogous components from the ecoinvent life cycle inventory database. Electricity grid mix and production locations were varied for each of the six main cases to illustrate the possible range of impacts across production locations.

Payback time methodology. We used a graphical approach for calculating EPBT and CPBT, which avoids shortcomings of typical methods in PV LCA literature by accounting for nonlinearity and avoiding data quality issues associated with long-term projections. We drew data from several sources and models to calculate EPBT and CPBT, including UPV energy generation modeled from the NREL System Advisor Model (NREL 2023), regional grid efficiency data from the U.S. Energy Information Administration, grid emission factors from the National Energy Technology Laboratory Grid Mix Explorer 4.2 (Skone 2020), and future grid mix projections from the NREL Cambium model (Gagnon et al. 2023a).

Results. Results are summarized in Table ES-1. CED results are reported here as megajoules of oil-equivalent primary energy required over the system lifecycle ($MJ_{oil\text{-}eq}$) per megajoule generated by the UPV system over its life (MJ_{UPV}). CED results show $MJ_{oil\text{-}eq}/MJ_{UPV}$ ratios at or below 0.1, which demonstrates efficient use of primary energy resources (below a 1:1 ratio) and represents a slight improvement over previous results in literature. CED is slightly higher for the low-carbon U.S. supply chain compared to the low-carbon imported supply chain because of the greater reliance on nuclear energy in the United States, which has greater primary energy demand. Conversely, GHG emissions across the U.S. supply chain are lower than those for the imported supply chain. In this study, GHG emissions per kilowatt-hour (kWh) range from 10 to 36 grams of carbon dioxide equivalent (g CO_2e), which is consistent with or lower than previous results published by NREL and the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS). Additionally, half of the six main cases meet requirements for the low-carbon ecolabel for solar PV modules created by the Global Electronics Council (less than 630 kg CO_2e per kW_{dc}), but only one case (low-carbon U.S. region) meets the criteria for the “ultra-low” carbon ecolabel (less than 400 kg CO_2e per kW_{dc}).

Interpretation. The interpretation of the LCA results produced estimates for payback times, as illustrated in Figure ES-1 for EPBT which was determined to vary from 0.5 to 1.2 years in the United States depending on the supply chain and installation location. The benchmark system EPBT was estimated to be 0.6 years, which is lower than recent updates from IEA-PVPS. CPBT was shown to vary from 0.8 years to almost 20 years in the United States depending on the supply chain and installation location, but is likely less than 14 years for the average supply chain even when installed in a low-irradiance location with a low-emission grid. The benchmark system was determined to have a CPBT of 2.1 years, which is on the lower end of estimates from recent literature (typically >2 years).

Table ES-1. LCA Results for the Six Main Cases Evaluated in This Report

	Installation Location	CED ($MJ_{oil\text{-}eq}/MJ_{UPV}$)	GHG per kWh	EPBT	CPBT
Low-carbon import, high recovery at EOL	Phoenix, AZ	0.05	11 g CO_2e	0.5 years	0.9 years
Average import, partial recycling at EOL	Fredonia, KS	0.07	19 g CO_2e	0.6 years	2.1 years
High-carbon import, landfill at EOL	Seattle, WA	0.12	36 g CO_2e	1.2 years	20 years
Low-carbon domestic, high recovery at EOL	Phoenix, AZ	0.05	10 g CO_2e	0.5 years	0.8 years
Average domestic, partial recycling at EOL	Fredonia, KS	0.07	14 g CO_2e	0.6 years	1.5 years
High-carbon domestic, landfill at EOL	Seattle, WA	0.10	30 g CO_2e	1.1 years	16 years

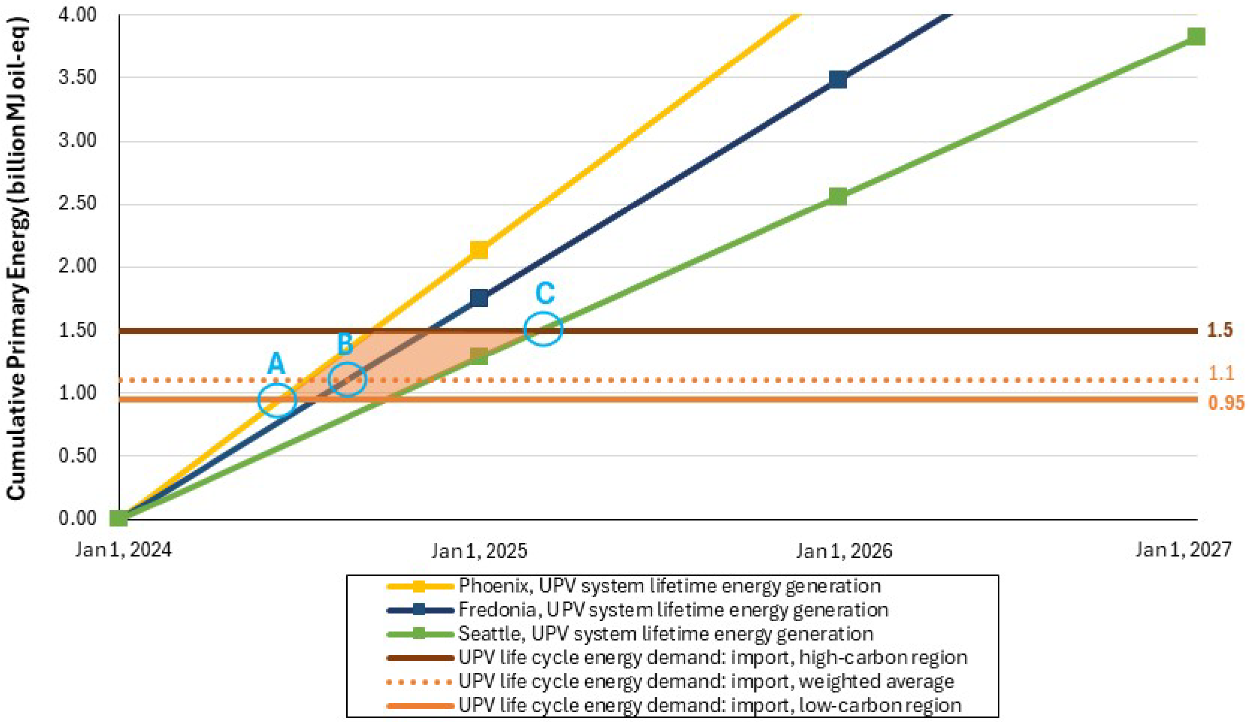

Figure ES-1. Energy payback time for 100-MW_{dc} UPV system installed in the United States

(A) Low-carbon imported modules installed in Phoenix, AZ; (B) Weighted-average imported modules installed in Fredonia, KS; (C) High-carbon imported modules installed in Seattle, WA.

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1 Introduction

The recent Solar Futures Study from the U.S. Department of Energy (DOE) estimated photovoltaics (PV) would play a large role in minimum-cost scenarios for decarbonizing the U.S. grid and the broader U.S. energy economy (Ardani et al. 2021). The report estimated that approximately 900 gigawatts direct current (GW_{dc}) of new PV systems are needed during 2020 to 2035 to achieve a decarbonized U.S. grid by 2035. It also estimated a total of roughly 3,800 GW_{dc} of new PV systems would be needed during 2020 to 2050 to decarbonize both the grid and the broader U.S. economy by 2050. This pace of deployment would correspond to more than a 4x increase over annual deployment rates prior to 2023.

In 2021, the Intergovernmental Panel on Climate Change (IPCC) estimated only 300–900 gigatons of carbon dioxide equivalent (CO_2e) can be emitted to remain below the 1.5°C target for global temperature rise (Masson-Delmotte et al. 2021). Given the estimated scale of PV deployment, an accurate assessment of the carbon intensity of PV systems can support more precise budgeting and help confirm how much of the remaining carbon budget will be consumed in their manufacture, use, and disposal (Goldschmidt et al. 2021; Wikoff, Reese, and Reese 2022).

Life cycle assessments (LCAs) are often used to estimate the total carbon emissions associated with the manufacture, use, and disposal of a given technology. Many PV LCAs exist already in the literature (Antonanzas, Arbeloa-Ibero, and Quinn 2019; Müller et al. 2021; Méndez et al. 2021), but frequent updates and iterations are necessary to reflect rapid technology, manufacturing, and market changes that occur in the PV industry. Regional iterations are also often valuable, given that certain technologies and trends can be more prevalent in different regions due to infrastructure or policy reasons.

In the United States, utility-scale photovoltaics (UPV) typically represent 60%–70% of annual installations (Feldman et al. 2023b). Similarly, the *Solar Futures Study* (Ardani et al. 2021) indicates that most U.S. PV installations projected through 2050 are likely to be utility scale. In the United States, UPV installations tend to use single-axis trackers (Feldman et al. 2023a) and large central inverters. About two-thirds of U.S. UPV systems used crystalline silicon modules in 2022, while about one-third used cadmium telluride modules (Feldman et al. 2023a). Given the prevalence of crystalline silicon UPV systems in the United States and their importance for future solar deployment, a dedicated LCA for U.S. systems with these features is warranted.

Finally, we can consider the supply chain for U.S. PV systems in the context of U.S. tax credits recently made available by the Inflation Reduction Act. These include both domestic manufacturing tax credits (48C/45X) and a deployment tax credit bonus for domestic content (48/48E/45/45Y). While the United States has largely relied on imported modules in recent years (Feldman et al. 2023b), the recent implementation of the Inflation Reduction Act motivates a prospective consideration of a domestic supply chain for the United States. Some existing LCA studies already evaluate this possibility (Anctil 2021; Anctil, Farina, and Yuan 2023; Gan et al. 2023; Liang and You 2023); however, this report examines the most common UPV system type in the United States in greater detail.

2 Methodology

The methodology guidelines for PV LCAs defined by the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) were heavily used in the creation of this LCA study (Frischknecht et al. 2020a). The life cycle assessment software openLCA version 2.0 (GreenDelta 2023) was used in the creation of this analysis because it is open source and compatible with many life cycle inventory databases such as ecoinvent and US-LCI. This section is organized according to the main steps in conducting an LCA, which typically include:

1. Goal, scope, system description
2. Inventory
3. Impact assessment
4. Interpretation and uncertainty analysis.

2.1 Goal, Scope, System Description

As stated in the introduction, the primary goal of this study is to provide an updated estimate of the embodied energy and embodied carbon associated with UPV systems installed in the United States. The study is scoped as a cradle-to-grave process-based LCA to evaluate cumulative energy demand (CED) and greenhouse gas (GHG) emissions, as well as energy payback time (EPBT) and carbon payback time (CPBT). It is scoped primarily as a retrospective attributional LCA; however, the options analyzed in this work may support its use as a short-term prospective or decisional LCA.

System description. The system under study is consistent with the benchmark utility-scale PV system defined in recent PV system benchmarks by the National Renewable Energy Laboratory (NREL) (Ramasamy et al. 2022). Here, we model a 100-MW_{dc} system that is fully installed and operational on January 1, 2024. The main components of this U.S. UPV system are illustrated in Figure 1. We assume the system uses monofacial monocrystalline silicon modules (1.99 m^2, 20.3% efficient, 405 watts under standard test conditions) containing passivated emitter and rear cells (PERC) mounted on a single-axis tracker. The system has an inverter loading ratio of 1.34, an annual system degradation rate of 0.7%, and a 30-year operational lifetime. We report results for a functional unit of kilowatt-hours (kWh), but results are sometimes also discussed in units of kilowatts direct current (kW_{dc}) (synonymous with the unit kilowatts peak often used in previous LCAs), or totals for a 100-MW_{dc} utility system.

The life cycle stages shown in Figure 2 are defined to be consistent with Frischknecht et al. (2020a). This includes product manufacturing, system construction (installation), use, and end of life (EOL). The individual processes shown below each stage are defined as the foreground processes within this LCA. Supporting inputs such as fuels, infrastructure, electricity mixes, and materials other than the silicon absorber comprise the background processes. We also evaluate certain options within the manufacturing, use, and end-of-life stages as noted in Figure 2. The full list of permutations for these options are presented in Table 1.

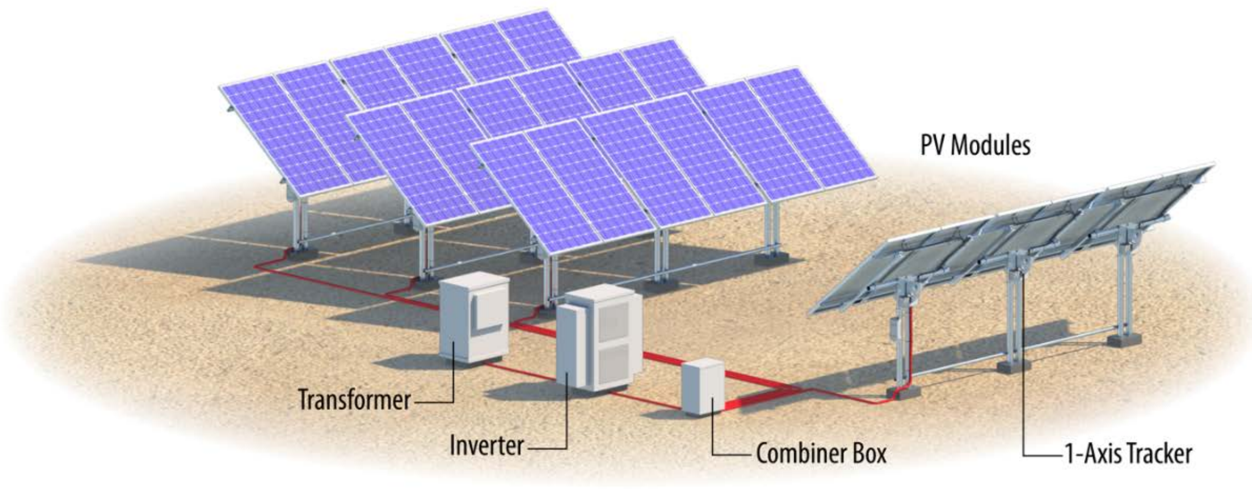

Figure 1. Illustration of the main components in a U.S. UPV system.

The first row is facing the opposite direction for illustration purposes.

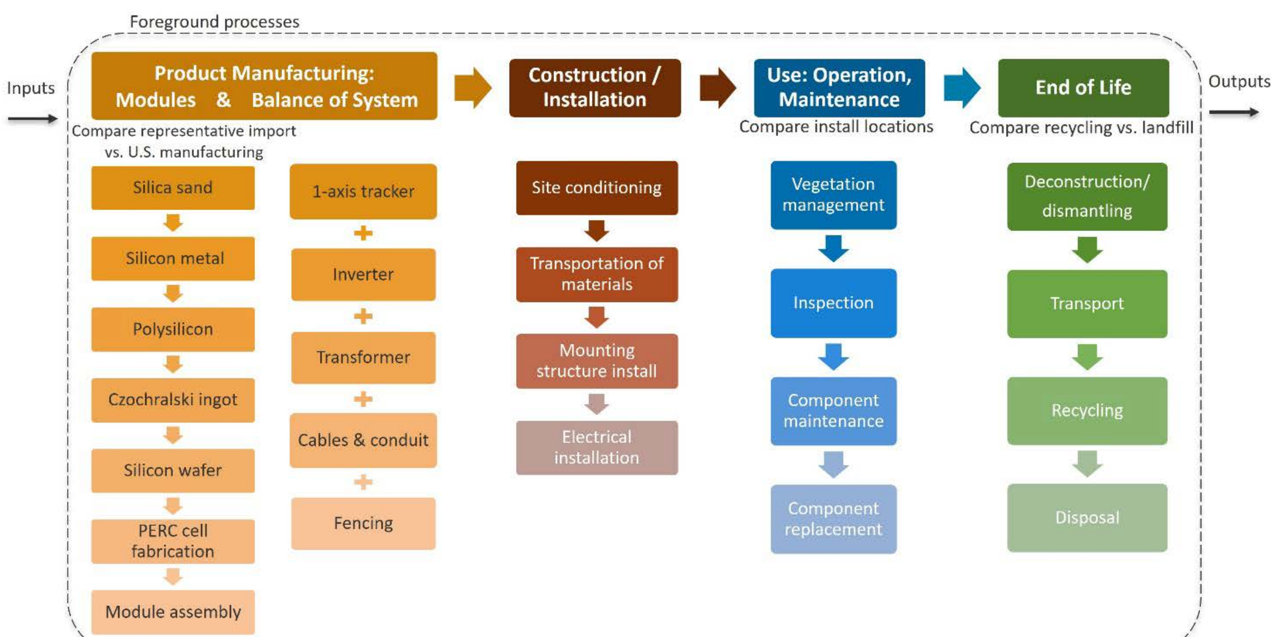

Figure 2. System diagram of foreground processes for the U.S. UPV system evaluated in this LCA

Table 1. Full List of Permutations for Life Cycle Options Defined in Section 2.1

Supply Chain Option	Manufacturing Location	Installation Location	End-of-Life Options (Defined in Section 3.5)	<u>**6 Main Cases**</u>
Imported PV modules	PV module manufacturing in **high-carbon** regions within China & southeast Asia Details in Section 3.1	Low-irradiance U.S. location (Seattle)	Landfill	High-carbon import
			Partial recycling	
			Hypothetical high recovery	
		Average-irradiance U.S. location (Fredonia)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		High-irradiance U.S. location (Phoenix)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
	PV module manufacturing in **average-carbon** regions within China & southeast Asia Details in Section 3.1	Low-irradiance U.S. location (Seattle)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		Average-irradiance U.S. location (Fredonia)	Landfill	Average import
			Partial recycling	
			Hypothetical high recovery	
		High-irradiance U.S. location (Phoenix)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
	PV module manufacturing in **low-carbon** regions within China & southeast Asia Details in Section 3.1	Low-irradiance U.S. location (Seattle)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		Average-irradiance U.S. location (Fredonia)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		High-irradiance U.S. location (Phoenix)	Landfill	Low-carbon import
			Partial recycling	
			Hypothetical high recovery	
Domestic PV modules	PV module manufacturing in **high-carbon** U.S. region Details in Section 3.1	Low-irradiance U.S. location (Seattle)	Landfill	High-carbon domestic
			Partial recycling	
			Hypothetical high recovery	
		Average-irradiance U.S. location (Fredonia)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		High-irradiance U.S. location (Phoenix)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
	PV module manufacturing in **average-carbon** U.S. region Details in Section 3.1	Low-irradiance U.S. location (Seattle)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		Average-irradiance U.S. location (Fredonia)	Landfill	Average domestic
			Partial recycling	
			Hypothetical high recovery	
		High-irradiance U.S. location (Phoenix)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
	PV module manufacturing in **low-carbon** U.S. region Details in Section 3.1	Low-irradiance U.S. location (Seattle)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		Average-irradiance U.S. location (Fredonia)	Landfill	
			Partial recycling	
			Hypothetical high recovery	
		High-irradiance U.S. location (Phoenix)	Landfill	Low-carbon domestic
			Partial recycling	
			Hypothetical high recovery	

Manufacturing options: PV module supply chains. We consider six primary PV module manufacturing options: three based on an imported supply chain, and three based on a domestic supply chain. More information on the data used to represent the regions within each supply chain is provided in Section 3.1. The three imported supply chain options are intended to reflect current U.S. imports and compare PV module manufacturing in:

- Low-carbon regions within China and Southeast Asia
- Average-carbon regions within China and Southeast Asia
- High-carbon regions within China and Southeast Asia.

The three domestic supply chain options compare PV module manufacturing in:

- A low-carbon U.S. region
- An average-carbon U.S. region
- A high-carbon U.S. region.

The imported supply chain options are meant to represent typical 2022 U.S. imports for silicon PV, whereas the domestic supply chain options represents a potential shift to a U.S.-based supply chain (see U.S. manufacturing announcements summarized in Feldman et al. [2023a]), which could be supported by the Inflation Reduction Act and other recent U.S. policies such as the Bipartisan Infrastructure Law.

Use options: installation location. Three different installation locations were evaluated to illustrate a range of irradiation conditions across the United States. More detail is provided in Section 2.4:

- Fredonia, Kansas, was selected as the average U.S. irradiation location to be consistent with the 2021 and 2022 NREL system cost benchmark reports (Ramasamy et al. 2021a; 2022).
- Seattle, Washington, was selected as the low U.S. irradiation location, which is consistent with the 2021 NREL system cost benchmark (Ramasamy et al. 2021a).
- Phoenix, Arizona, was selected as the high U.S. irradiation location, which is consistent with the 2020 NREL system cost benchmark (Feldman et al. 2021).

It should be noted that there are locations in the United States with higher and lower irradiance than those chosen here. However, these locations were selected to represent a range of U.S. grid mixes and create a range of carbon payback times. Using the grid mix projections described later in this report, Phoenix represents a relatively high-carbon U.S. grid, Seattle represents a relatively low-carbon U.S. grid, and Fredonia falls somewhere in the middle. This is discussed in more detail in Section 2.4 and later in Section 5.

EOL options. Due to the uncertainty around EOL protocols 30 years into the future, multiple EOL options are considered. Landfilling, partial recycling, and hypothetical high-recovery recycling were evaluated to capture a range of EOL outcomes. Greater detail is provided in Section 3.5. Additionally, EOL accounting (allocation) methods were evaluated for each option, where the cutoff approach was compared to the avoided burden (AB) approach per recommendations from Frischknecht et al. (2020a).

2.2 Inventory

The methods for collecting life cycle inventory data are described in this section. Different approaches were used depending on the availability of data in literature and whether a process was categorized as a foreground process or a background process. Detailed discussions of foreground inventories are presented in Section 3. The full inventories and reference for each data point are available in Appendix A, including information on data quality and limitations.

Foreground processes. The foreground processes considered in this LCA include silica sand, silicon metal, polysilicon, single-crystal ingots, wafers, PV cells, modules, single-axis trackers, inverters, transformers, and other balance-of-system (BOS) components, as well as installation, maintenance, and EOL stages as shown in Figure 2. Compilation of life cycle inventory data began with a literature review prioritizing PV LCAs published since 2018 (Frischknecht et al. 2020b; Heidari and Anctil 2022; Lunardi et al. 2018; Müller et al. 2021; Méndez et al. 2021; Danelli et al. In Review; Leccisi, Lorenz, and Fthenakis 2023; Antonanzas, Arbeloa-Ibero, and Quinn 2019; Pu et al. 2021). However, EOL LCAs drew from earlier publications (Stolz et al. 2017; Ravikumar et al. 2016; Latunussa et al. 2016). Other studies, such as circular economy material flow studies (Brailovsky et al. 2023; Bartie et al. 2021), industry advances, and best practices (Walker 2018; Chen et al. 2016; Curtis et al. 2021b; International Finance Corporation 2015) were reviewed for verification of modern installation projects, material demands, and process energy intensities. Data from different publications were compared whenever applicable, and critical processes (e.g., polysilicon energy inputs, concrete use for system install, etc.) were reviewed with industry professionals. Based on these assessments and expert review, final inventories were compiled for this study.

Empirical inverter inventory. The inverter inventories available in literature relied on data collected prior to 2005 and did not reflect the size typically used in modern U.S. UPV installations (500-kW vs. multi-megawatt installations). To address this literature shortcoming, we evaluated a commercially-available inverter rated at 2.7 MW_{ac} and manufactured in 2022 to collect original empirical inventory data. Using this assembled, preoperational inverter and associated documentation, we inventoried internal components, external connections, and inverter housing and mounting. For bulk material inputs (such as conductors, insulators, structural supports), measurements were taken and used to calculate a total quantity of material. For complex components (i.e., inductors, capacitors), weight and part counts were estimated and the best approximate inventories in the ecoinvent 3.9 database were used.

EOL processes. As mentioned in Section 2.1, multiple EOL options were considered due to the uncertainty around EOL protocols 30 years into the future. Additionally, a cutoff approach is compared to an avoided burden approach to illustrate the effects of using environmentally preferable EOL treatment options. In the openLCA software, these inventories were built using the "material flow logic" approach (also described as the "actual flow direction" approach), which means the inventory must be designated as a "waste treatment process" when initially created in the software. Then, subsequently:

- To employ the avoided burden approach, any high-value outputs are designated as "avoided products" to receive credit for offsetting virgin material demand for those products (e.g., glass cullet).

- To employ the cutoff approach, no outputs are designated as "avoided products."

Background processes. Background processes in this LCA encompass non-silicon material supply chains and process materials (e.g., polymers, alloys, solvents), infrastructure, fuels, and grid electricity. Inventories for background processes were sourced from ecoinvent 3.9.1 (FitzGerald and Sonderegger 2022).

2.3 Impact Assessment

The life cycle impact assessment uses the inventories to quantify environmental impacts, which are typically resource and energy consumption or emissions. The main metrics considered for this LCA are CED and GHG emissions.

For energy generation technologies, CED can assess how efficiently the system uses energy resources. CED is typically assessed in units of megajoule of oil equivalent ($MJ_{oil\text{-}eq}$) primary energy, across all energy source types (renewable and nonrenewable). To calculate CED in these units, the total energy content high heat value impact factors were used from the ecoinvent 3.9 database. Nonrenewable CED (nr-CED) is also reported for fossil and nuclear energy sources (using nonrenewable energy content high heat values from ecoinvent 3.9) following guidance from (Raugei et al. 2021) to provide better insight into how sustainably the system uses primary energy resources.

To assess the impact of UPV systems on the remaining carbon budget, GHG emissions are quantified in kilograms of carbon dioxide equivalent (kg CO_2e) using IPCC global warming potential (GWP) factors from 2021. The baseline model for 100 years (GWP100) was selected following the recommendation of the IEA-PVPS PV LCA methodology guidelines (Frischknecht et al. 2020a).

This report also catalogues wastes in the inventory for each foreground process in Appendix A. These differ from EOL waste flows, which are reported as separate inventories. Output wastes for the manufacturing foreground processes can be considered as manufacturing emissions or scrap produced during the manufacturing phase, not at EOL.

2.4 Interpretation

This study uses the life cycle impact assessment results to evaluate EPBT and CPBT of the UPV system, which are defined in the following subsections. To calculate EPBT and CPBT, certain assumptions and information regarding the operation and use phase of energy generation technologies are required outside of what is available in the life cycle inventory and life cycle impact assessment analyses. The information and methods necessary for EPBT and CPBT calculations are presented in detail in the following subsections.

In this report, both EPBT and CPBT were analyzed for three installation locations to represent a range of U.S. insolation and grid mixes to illustrate the feasible ranges for EPBT and CPBT across the United States. Regional conditions and other factors that influence payback times are reported in Table 2. EPBT is primarily affected by the local irradiance and grid efficiency, while CPBT is affected by irradiance, local grid emission, and projected grid mix. An area with a high-emission grid is estimated to produce a shorter CPBT because the PV is offsetting a highemitting grid, whereas the low-emission grid is expected to produce a longer CPBT because the PV is offsetting an already low-emitting grid.

Table 2. Payback Time Installation Location Parameters

	Low Payback Time	Mid-Case	High Payback Time
Location	Phoenix, AZ	Fredonia, KS	Seattle, WA
Irradiation	High	Medium	Low
Local Grid Emissions, 2022	Medium	High	Low
Grid Efficiency	Medium	Low	High
Grid Mix Projections: *NREL Cambium 2022 Scenarios for Projected Renewable Energy (RE) Capacity Costs*	High RE technology cost scenario	Mid-case scenario	Low RE technology cost scenario

In this report, we use a payback time methodology which is not typically used in PV LCA literature. The method used in this report avoids some shortcomings of more typical payback time methodologies, by not incorporating uncertainty over the long-term operation of PV systems. The method in this report also captures nonlinearity in time-dependent variables, unlike the more typical payback time methodology. The following subsections describe the most commonly used payback time method in PV LCA literature, its shortcomings, and an alternative graphical approach.

2.4.1 Energy Payback Time

EPBT for any energy-generating technology can be defined as the length of time the technology must operate before it produces the amount of energy required by the system throughout its life cycle (manufacturing, use, and EOL). EPBT is often used as a metric to assess and compare the energy balance of energy generation technologies. For example, if the EPBT of a PV system is 4 years, then the PV system has recovered all the energy needed for its life in 4 years, and the system is going to produce additional energy for its remaining life (i.e., 26 years, assuming a PV system lifetime of 30 years).

EPBT is operationalized as the ratio of the total primary energy input during the system life cycle (CED) and the primary yearly energy generation during system operation (Alsema 1998; 2012; Frischknecht 2020a; Raugei et al. 2021). Mathematically it can be formulated as follows:

$$EPBT_{PV} = \frac{\left(E_{manuf} + E_{inst} + E_{EOL}\right)}{\frac{\left(\sum_y \left(\frac{E_{agen,y}}{\eta_{G,y}} - E_{O\&M,y}\right)\right)}{Y}} \tag{1}$$

where:

- E_{manuf} is primary energy demand (in $MJ_{oil\text{-}eq}$) to manufacture the PV system

- E_{inst} is primary energy demand (in $MJ_{oil\text{-}eq}$) to construct and install the system
- E_{EOL} is primary energy demand (in $MJ_{oil\text{-}eq}$) for EOL management
- $E_{agen,y}$ is annual electricity generation (in kWh) for each year of its life, y
- $E_{O\&M,y}$ is annual primary energy demand (in $MJ_{oil\text{-}eq}$/year) for operation and maintenance for each year of its life, y
- $\eta_{G,y}$ is grid efficiency, the electricity to primary energy conversion efficiency at the demand side (kWh electricity per $MJ_{oil\text{-}eq}$) for each year of its life, y
- Y is the total life of the system in years (assumed to be 30 years).

To calculate the primary energy input during the system life cycle, or the numerator in the EPBT formulation shown in Equation 1, results from life cycle inventory are used (see Section 3). We use NREL's System Advisor Model to calculate the annual system generation data $E_{agen,y}$ for a 100-MW_{dc} utility system (NREL 2023). The system characteristics are described in detail in (Ramasamy et al. 2021b). To capture variability in irradiation levels, the PV system was assumed to be installed in three locations: Fredonia, Seattle, and Phoenix. Table 3 lists the system characteristics, and Figure 3 shows the 30-year annual electricity generation of the system modeled using the System Advisor Model (NREL 2023). Annual generation by year is also tabulated in Appendix B.

Table 3. Utility-Scale PV System Characteristics

Category	Value
First year of operation	2024
System size	100 MW_{dc} – a large, single-axis tracking utility-scale system capacity
Module efficiency	20.3% – national average silicon module efficiency
Module power	405W_{dc} – rated module power under standard test conditions (STC) module efficiency × module area × average radiation under STC = 20.3% × 1.99 m^2 × 1,000 W_{dc}/m^2 = 405 W_{dc}
Location	Baseline/Average: Fredonia, KS Low: Seattle, WA High: Phoenix, AZ
Inverter loading ratio	1.34
Inverter efficiency	96%
Annual AC degradation rate	0.7%
Grid efficiency η_G (MJ per primary energy $MJ_{oil\text{-}eq}$)	35.24% (2021 U.S. average) 34.9% (2019 Arizona) 35.5% (2019 Washington) 32.3% (2019 Kansas)

Grid efficiency is a factor used to convert the electricity generated by the UPV system to its primary energy equivalent. The units for grid efficiency, η_G, are kilowatt-hours of electricity per megajoule of oil equivalent ($MJ_{oil\text{-}eq}$). To calculate η_G, a ratio to convert energy demand (kWh) to primary energy ($kWh_{oil\text{-}eq}$) was first sourced via literature. Lawrence Livermore National Laboratory (LLNL 2022) uses EIA Monthly Energy Review (EIA 2023) data to calculate the ratio of energy demand to primary energy. The ratio was then multiplied with a conversion factor of 0.2778 kWh/MJ to get η_G in kWh/MJ$_{\text{oil-eq}}$. For the year 2021, U.S. grid efficiency in kWh/kWh$_{\text{oil-eq}}$ was calculated to be 35.24%. As grid efficiency increases, EPBT will increase over time and can have significant impact on the EPBT estimate (Raugei 2013). Depending on the location of the PV system, grid efficiency can change. While city-level grid efficiency data are not available, state-level data are available for the year 2019 (LLNL 2022). Data on temporal variation in grid efficiency based on expected changes in grid mix are not available and not modeled.

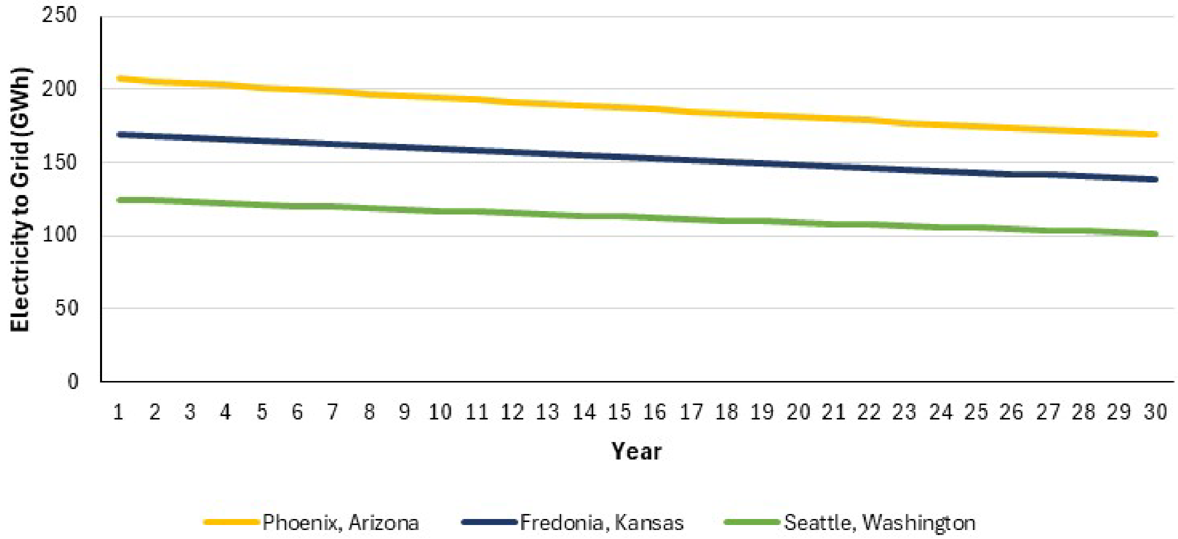

Figure 3. Electricity generated by the UPV system described in Table 3 (data in Appendix B)

2.4.2 Carbon Payback Time

CPBT, like EPBT, calculates the amount of time a system takes to produce enough electricity to offset the total amount of carbon emitted by the system over its life cycle (manufacturing, use, and EOL). CPBT is operationalized as the ratio of total GHGs emitted during the life of the PV system and GHG emissions avoided from the electricity produced by the system. This is described in Equation 2.

$$CPBT = \frac{(C_{manuf} + C_{inst} + C_{use} + C_{EOL})}{\frac{\left(\sum_y \left(E_{agen,y} \times EF_{G,y}\right)\right)}{Y}} \qquad (2)$$

where

- C_{manuf} is GHG emitted (in g CO_2e) to manufacture PV system
- C_{inst} is GHG emitted (in g CO_2e) during construction and installation of the system
- C_{EOL} is GHG emitted (in g CO_2e) during end-of-life management
- C_{use} is GHG emitted (in g CO_2e) during operation and maintenance
- $E_{agen,y}$ is annual electricity generated by the plant (in kWh) each year of its life, y

- $EF_{G,y}$ is emission factor of the grid (g CO_2e avoided per kilowatt-hour of electricity) for each year of its life, y.

The scope and methodology used to calculate GHG emitted during the life cycle of the PV system (numerator in Equation 2) is discussed in Section 3. Average annual GHG avoided is calculated as the mean of the product of total electricity generated by the PV system (in kWh) and the emission factor of the electricity grid (in g CO_2e/kWh), the generated electricity that is potentially replaced.

The National Energy Technology Laboratory (NETL) Grid Mix Explorer version 4.2 was used to calculate the emission factor $EF_{G,y}$ of the local grid (Skone 2020). The Grid Mix Explorer is a tool that allows users to specify a grid mix and generates resulting life cycle inventory and impact data of the grid. State-level grid mixes for the respective install locations in this analysis were identified using the NREL Cambium model between 2023 to 2050. To capture uncertainty and variability in the evolving grid mix, the following three scenarios were selected; see the Cambium model documentation for further information about the scenario assumptions (Gagnon, Cowiestoll, and Schwarz 2023). For all the following scenarios, the Inflation Reduction Act Investment Tax Credit and Production Tax Credit are assumed to not phase out.

- *Mid-Case:* the model assumes central estimates for inputs such as technology costs, fuel prices, and demand growth. Electric sector policies are as they existed in September 2022, and it does not include nascent technologies.
- *Low Renewable Energy (RE) and Battery Costs:* the same set of base assumptions as the mid-case scenario, but where renewable energy and battery costs are assumed to be lower according to NREL's Annual Technology Baseline.
- *High Renewable Energy and Battery Costs:* the same set of base assumptions as the mid-case scenario, but where renewable energy and battery costs are assumed to be high.

Not all technologies defined in Cambium match one-to-one with technologies modeled in the NETL Grid Mix Explorer technology. See Appendix C for the assumptions used to match the technologies between the two tools to quantify the grid mix as a percent of total electricity generation. The Grid Mix Explorer uses these values to calculate the emission factor as kg CO_2e per MWh of delivered electricity. To be consistent with life cycle impact assessment methodology discussed in Section 3, the NETL Grid Mix Explorer was updated with the GWP of greenhouse gases based on the IPCC's sixth assessment report. Grid Mix Explorer Version 4.2 uses the GWP from the IPCC's fifth assessment report. See Appendix C for the GWP numbers that were manually updated in the tool. Grid mixes for the three locations are also presented in Appendix C. The associated emission factors for the grid are shown in Table 4.

Table 4. Average Emission Factors for the Years 2024 to 2050 Calculated Based on Generation Data from Cambium and Emission Factors from NETL's Grid Mix Explorer

Cambium outputs grid mix data every 2 years until 2030 and every 5 years until 2050. Data after 2035 are not required due to the graphical approach taken in this report (see Section 2.4.3). Data for missing years are calculated by interpolation.

Year	Kansas – Mid-Case (kg CO_2e per MWh)	Washington – Low Renewable Energy & Battery Costs (kg CO_2e per MWh)	Arizona – High Renewable Energy and Battery Costs (kg CO_2e per MWh)
2024	282	89	345
2025	208	74	336
2026	133	60	327
2027	107	55	319
2028	81	51	310
2029	78	48	280
2030	75	46	249
2031	73	46	244
2032	71	47	239
2033	69	47	233
2034	67	48	228
2035	65	48	223
2036	63	48	216
2037	60	48	209
2038	58	48	202
2039	56	48	195
2040	54	48	188
2041	52	48	180
2042	51	48	172
2043	49	48	163
2044	48	49	155
2045	47	49	147
2046	46	49	141
2047	45	49	135
2048	44	50	128
2049	44	50	122
2050	43	50	116

2.4.3 Challenges in Typical Methodology

The methods for calculating EPBT and CPBT previously discussed rely on averaging annual energy generation and avoided carbon over the lifetime of the system, which introduces two key challenges:

1. It does not reflect effects of nonlinearity in the data, e.g., energy generation by the UPV plant is higher in early years and then decreases in later years due to degradation. Similarly, the carbon emission factor of the grid and grid efficiency can also vary over the years depending on the new electricity generators installed and older electricity generators replaced.
2. Averaging over the life of the system incorporates many projected assumptions for later years, which have higher degrees of uncertainty, particularly around estimating future grid efficiency and the carbon emission of the grid. This uncertainty is due to several reasons, including uncertainty about the future grid mix, uncertainty about future efficiency improvements of energy-generating technologies, and uncertainty about future data related to calculating life cycle inventory for technologies installed in the future.

The combination of these two challenges can cause large uncertainty in the payback time estimates. For example, in EPBT calculations, the average annual primary energy displaced by a UPV solar plant is calculated as a product of grid efficiency and energy replaced for the respective years. Grid efficiency data are based on the year 2019 and assumed to be static, and energy replacement data are modeled estimates.

2.4.4 Graphical Approach

A graphical approach can reduce both nonlinearity and data quality challenges. In this approach, EPBT or CPBT is calculated by finding the point of intersection between the total embodied energy or carbon during the system life cycle and the cumulative amount of primary energy/carbon displaced by the system, as illustrated in Figure 4. The advantage of this method compared to the equations discussed earlier is its reduced data requirement, i.e., any data on cumulative energy generated or carbon avoided are not needed after the point of intersection. This is important because the quality of modeled data decreases for projections further in the future, since it is hard to predict the emission factor of the grid ($EF_{G,y}$) and grid efficiency ($\eta_{G,y}$).

Further, by plotting cumulative primary energy and avoided carbon nonlinearly, calculating annual averages is not required. For example, in Figure 4 the dashed line shows the modeled cumulative energy/carbon estimates calculated using the typical approach, i.e., an annual average. The blue line shows the cumulative energy/carbon estimates when nonlinearity is considered. Both methods result in the same cumulative energy generation or emissions, as seen on the right side of each graph. However, the point of payback time occurs earlier for the blue lines, where it intersects the red lines representing the embodied energy/carbon value. We can also expect more nonlinearity in the data to have larger impact than shown in the illustration.

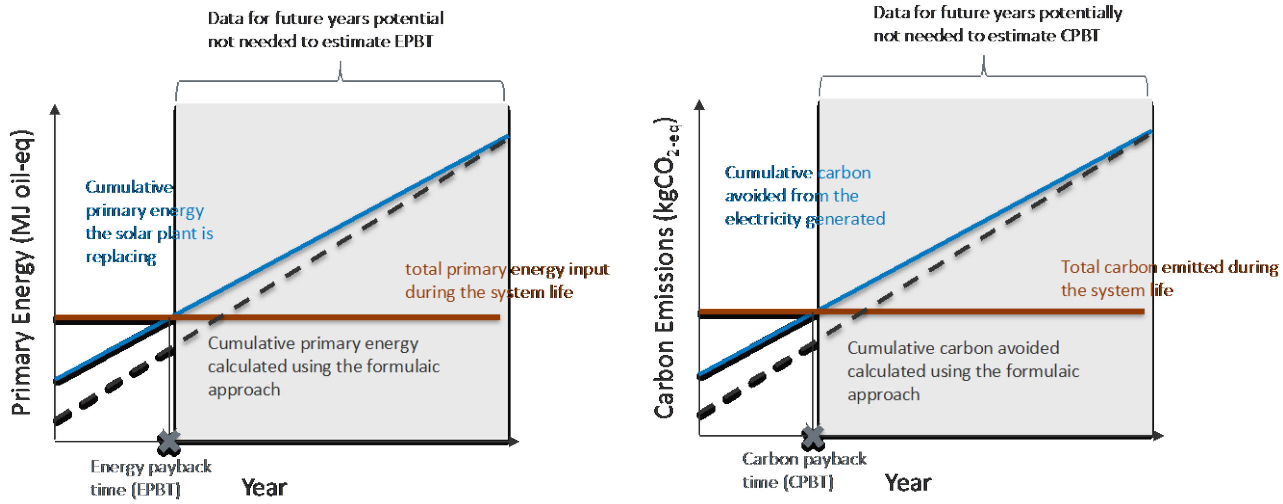

Figure 4. Illustration of graphical method to estimate payback time

This graphical method can also be represented as an equation similar to the method defined in Yang and Suh (2015) by solving for the minimum y value that satisfies the following inequality:

$$\left(C_{manuf} + C_{inst} + C_{use} + C_{EOL}\right) \leq \sum_{y} \left(E_{agen,y} \times EF_{G,y}\right), y = \{0, 1, 2, \dots\} \qquad (3)$$

3 Inventory

This section discusses the literature and data used to build the inventories for this LCA, while the methodology used to build the inventories is described in Section 2.2. The full inventories and reference for each data point are available in Appendix A, as well as information on data quality and limitations.

3.1 Electricity Mixes

We discuss the use of electricity mixes first because they recur throughout many foreground processes discussed later. Due to the range of grid mixes possible in China, the United States, and Southeast Asia (as well as uncertainty regarding the regions for both manufacturing and deployment), we evaluated weighted national averages in addition to low-emission regions and high-emission regions to illustrate the ranges of embodied energy and carbon that may be achievable.

The ecoinvent 3.9.1 database contains an inventory for the national weighted average Chinese grid; it also includes inventories for seven different grid regions within China using information from 2020. The GHG emissions per megajoule from these different grid regions are shown in Figure 5. The region with the most emission-intensive grid is the northeast grid (NECG), and the region with the least emission-intensive grid is the southwest grid (SWG) (FitzGerald and Sonderegger 2022). It should be noted that while the northwest grid (NWG) falls within this range, imports to the U.S. should not be originating from this region due to the U.S. Uyghur Forced Labor Protection Act (UFLPA).

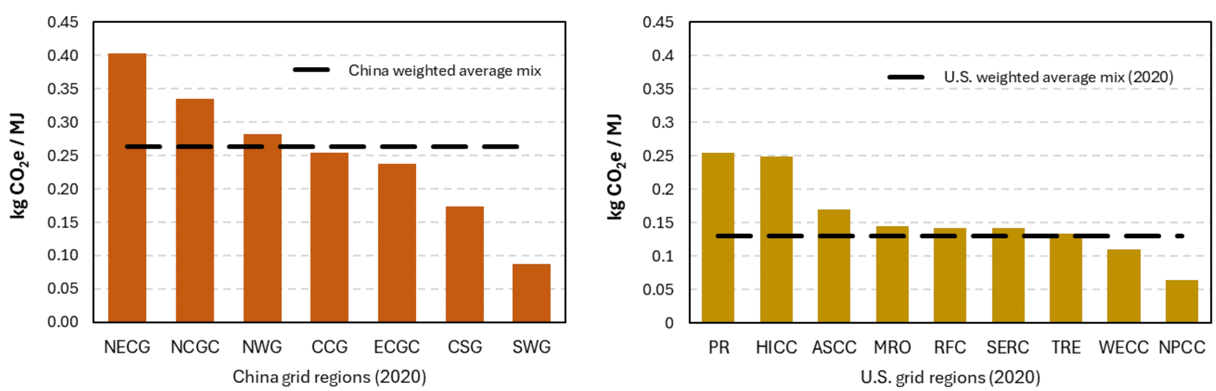

Figure 5. GHG emissions per megajoule of electricity, for the different grid regions available in ecoinvent 3.9 for China and the United States

However, due to anti-dumping and countervailing duties on cell and module imports from China, U.S. imports of cells and modules primarily originate from other countries near China (primarily in Southeast Asia). The top countries in 2022 were Malaysia, Vietnam, and Thailand (Feldman et al. 2023a). The ecoinvent database had weighted national average grid mixes for Malaysia, Thailand, and Vietnam. The GHG emissions for these different grids are shown in Figure 6, where the Malaysian grid has the highest emissions, Vietnam has the lowest, and Thailand falls in between. Table 5 reports the grid regions selected to create the three imported supply chain cases.

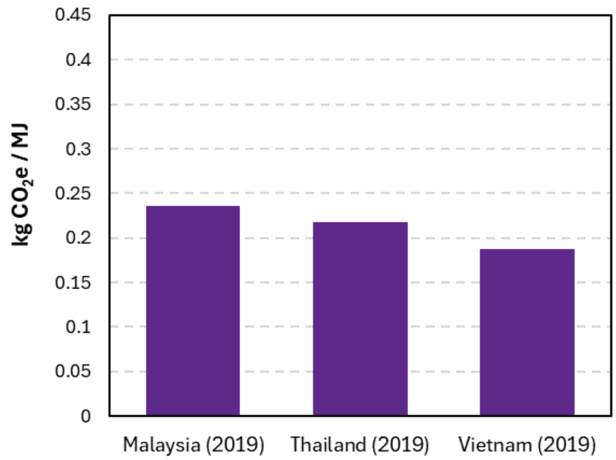

Figure 6. GHG emissions per megajoule of electricity for Malaysia, Thailand, and Vietnam national averages in ecoinvent

Table 5. Electricity Grid Mix Sensitivity Analysis for Imported Supply Chain

Imported cases:	Low emission	Average emission	High emission
Silica sand	Imports from Cambodia [Heidari & Anctil 2022]	Weighted mix: Australia, Cambodia, Malaysia, Pakistan [Heidari & Anctil 2022]	Imports from Australia [Heidari & Anctil 2022]
Silicon metal	ecoinvent data for **Southwest China** grid	Weighted national average for **China**	ecoinvent data for **Northeast China** grid
Polysilicon	ecoinvent data for **Southwest China** grid	Weighted national average for **China**	ecoinvent data for **Northeast China** grid
Ingots & Wafers	ecoinvent data for **Southwest China** grid	Weighted national average for **China**	ecoinvent data for **Northeast China** grid
PERC cell fabrication	Weighted national average for **Vietnam**	Weighted national average for **Thailand**	Weighted national average for **Malaysia**
Module assembly	Weighted national average for **Vietnam**	Weighted national average for **Thailand**	Weighted national average for **Malaysia**

Similarly, the ecoinvent 3.9.1 database includes an inventory for the national weighted average U.S. grid from 2020, as well as inventories for nine different U.S. regions (ecoinvent 2023). The GHG emissions per megajoule from these different grid regions are also shown in Figure 5. The region with the most emission-intensive grid is Puerto Rico (PR), and the least emission-intensive grid region is the Northeast Power Coordinating Council (NPCC). These two grid regions were used to create Table 6, which summarizes the U.S. grid regions selected to create the domestic supply chain cases. The ecoinvent inventories for the U.S. grid regions show relatively good agreement with other recent U.S. regional grid assessments such as Anctil, Farina, and Yuan (2023). In particular, the ecoinvent NPCC emissions are similar to the lowest-emission U.S. grid region reported in Anctil, Farina, and Yuan (2023), attributed to the New York Upstate region of the NPCC. Average U.S. grid emissions reported in Anctil, Farina, and Yuan (2022) are approximately 20% higher than the average reported by ecoinvent, which underlines the need to assess the full range of U.S. regions in this study due to temporal and geographic uncertainty.

Table 6. Electricity Grid Mix Sensitivity Analysis for Domestic Supply Chain

Domestic cases:	Low emission	Average emission	High emission
All PV module supply chain processes	ecoinvent data for **U.S. NPCC** grid	Weighted national average for **U.S.**	ecoinvent data for **U.S. PR** grid

3.2 Manufacturing

Silica sand and silicon metal. For silica sand extraction and processing into silicon metal (also referred to as metallurgical-grade silicon or mg-silicon), updated inventories from literature were used (Heidari and Anctil 2022; Méndez et al. 2021; Chen et al. 2016; 2017). For the imported supply chain cases in this report, we used the legally imported silica sand data from Heidari and Anctil (2022) as reported in Table 5. For our domestic supply chain cases, we used the high-quality silica sand processing inventory available in Heidari and Anctil (2022). For silicon metal production, the inventory was primarily sourced from Heidari and Anctil (2022), which is similar to the ecoinvent 3.9 inventory and agrees with other recent studies such as Saevarsdottir, Magnusson, and Kvande (2021). However, we modified this inventory by replacing the "silicone plant" with an "electric arc furnace" as recommended by Méndez et al. (2021). For silicon metal produced in China, electricity use was assumed to be slightly higher based on data available from Chen et al. (2016; 2017).

Polysilicon. The inventory data for polysilicon production was primarily sourced from Méndez et al. (2021) and Müller et al. (2021). These data were reviewed with an industry expert for alignment with current industry trends. Ultimately, material inputs were used from Méndez et al. (2021), and energy inputs were sourced from Müller et al. (2021).

Single-crystal ingot. Two studies were primarily used to assemble updated our inventory for the Czochralski ingot growth process (Müller et al. 2021; Frischknecht et al. 2020b). Upon comparison, we found the inventory from Müller et al. (2021) was either approximately half (with the exception of electricity input, which was 18% higher), or an order of magnitude smaller than the inventory in Frischknecht et al. (2020b), which may be slightly dated, as some data points rely on references from 2011 or 2014. However, it should be noted there appears to be a typo in the inventory from Müller et al. (2021): the polysilicon input quantity seems as if it may be swapped with the ingot input quantity to the wafering process. This is also commented on briefly in Leccisi, Lorenz, and Fthenakis (2023). For this reason, our ingot inventory relies on the polysilicon input from Frischknecht et al. (2020b) and the remainder of the inventory from Müller et al. (2021).

Wafering. Our inventory for wafering also relies primarily on Müller et al. (2021) and Frischknecht et al. (2020b). Upon comparison, a similar pattern was seen where Müller et al. (2021) data were either the same, half, or an order of magnitude smaller than the IEA-PVPS Task 12 data. Specifically, the electricity and natural gas (heat) were half, and the materials associated with the diamond wire saw were an order of magnitude smaller. We note here that an updated inventory of diamond wire saw manufacturing would be a valuable addition to the literature, as most studies cite data prior to 2014 (before diamond wire saw became the primary wafering technology), and the literature may benefit from a better understanding of differences between electroplated and resin-bonded diamond wire. The final wafer inventory relies on the ingot input quantity from Frischknecht et al. (2020b), and the remainder of the inventory relies on Müller et al. (2021).

PERC cell fabrication. To reflect the dominant technology in the recent market, we looked for PERC cell fabrication inventories, since this cell type gained majority market share in 2019 (ITRPV Working Group 2020). Therefore, we rely on cell inventory data from Müller et al. (2021), which is largely corroborated by another PERC life cycle inventory (Danelli et al. In Review), with the exception of heat use. The amount of heat cited in Müller et al. (2021) appears to be 2 orders of magnitude larger than the PERC cell inventory in Danelli et al. (In Review) and the cell inventory in Frischknecht et al. (2020b), which represents the aluminum back surface field architecture that was dominant before PERC. The CED and GHG impacts from heat use in the Müller et al. (2021) inventory represent 2%–3% of impacts from the cell process (excluding wafer and other foreground processes). For this reason, we retain this value in our inventory but advise future efforts to assess this with empirical data if available. Additional ocean freight transportation estimated from Frischknecht et al. (2020b) is applied in the imported supply chain cases to account for cell and module production in Southeast Asia due to U.S. tariff policy.

Module assembly. The inventory for module assembly again relies primarily on Müller et al. (2021), which demonstrates good agreement with other contemporary literature such as Danelli et al. (In Review) and Yuan and Anctil (2022), though with slightly higher copper and lead use.

Single-axis tracker. We relied on a recent single-axis tracker inventory from literature (Antonanzas, Arbeloa-Ibero, and Quinn 2019), which was generated in cooperation with an industry partner. This represents a significant update over the ground-mount racking recommended in Frischknecht et al. (2020b), which is fixed tilt and uses concrete foundations; recent discussions with developers indicated concrete foundations are not common and are generally avoided unless required for difficult terrain. It also represents an update over a prior tracker inventory published in Sinha et al. (2013), which contains twice the amount of steel and aluminum and omits material for actuators. While Sinha et al. (2013) include cabling for the tracker, this is not mentioned in the inventory from Antonanzas, Arbeloa-Ibero, and Quinn (2019). This may be due to the inclusion of the ecoinvent "photovoltaics, electric installation" process in Antonanzas, Arbeloa-Ibero, and Quinn (2019), which primarily represents cabling.

Inverter. Empirical data were collected from a utility-scale inverter, rated for approximately 2.7 MW_{ac}. This inverter was selected because it is more representative of what is used in the U.S. market (>2 MW_{ac}). The inventory information collected was reviewed with technology experts and is reported in aggregate to avoid representing a single producer or inverter design. This represents a significant update to the largest inverters most commonly cited in PV LCA literature (Mason et al. 2006; Jungbluth et al. 2012), which are based on data collected prior to 2012 from inverters smaller than 1 MW. Quantities of bulk materials (copper, steel, aluminum, fiberglass, and concrete) were estimated to be roughly an order of magnitude lower than prior inventories in literature; however, since we relied on existing inventories in the ecoinvent 3.9 database for components like cables and fans, the materials in those components are not reported in the bulk material totals. Existing inventories in the ecoinvent 3.9 database were also used for components such as capacitors and inductors; however, it should be noted that the ecoinvent inventories are based on much smaller components than those used in a 2.7-MW_{ac} inverter and may introduce some inaccuracies regarding material and energy use.

Transformer. The inventory for the transformer is primarily based on data derived from Mason et al. (2006), which is roughly consistent with inventory reported by (Antonanzas, Arbeloa-Ibero, and Quinn (2019). However, the data for the concrete pad were updated to match the empirical inverter inventory in this report because identical pads were observed for the transformer during empirical inverter data collection.

Other balance-of-system components. The inventory for "electrical installation" was referenced from Méndez et al. (2021) because it contains relatively recent empirical data from a large ground-mount system. This primarily represented cables, conduit, and other electrical connection components. An inventory for fencing was used from Antonanzas, Arbeloa-Ibero, and Quinn (2019). The detailed BOS inventory in Wang et al. (2022) was reviewed but ultimately not selected for this report due to its focus on rooftop installations.

3.3 Construction and Installation

In this report, we define the installation phase of the life cycle to primarily capture site conditioning, delivery (transportation) of components, and energy used for installation of components. Empirical diesel use for site conditioning and installation was referenced from Antonanzas, Arbeloa-Ibero, and Quinn (2019). The transportation of components is primarily based on Frischknecht et al. (2020b). Truck and rail are applied for all components; however, ocean freight is also applied for modules in the imported supply chain cases (based on Asia-Pacific shipping distance defined in Frischknecht et al. (2020b). Land occupation is also considered per Méndez et al. (2021), and uses a 33% ground coverage ratio, which is the total surface area of modules divided by the total land area within the fence for the system.

3.4 Use Phase: Operation and Maintenance

The inventory for the use phase of the UPV system is collected from multiple data sources. Array cleaning was omitted based on infrequency described in the NREL operations and maintenance cost model (Walker 2018). Gasoline use for vegetation management is estimated from Sinha and de Wild-Scholten (2012). The replacement of 0.05% of PV panels per year is recommended by Klise, Lavrova, and Gooding (2018). Results published in Danelli and Brivio (2022) reported an actuator replacement rate of 35% over a 35-year system life. Maintenance (primarily lubrication) and replacement of other tracker components are not currently reported in literature (Antonanzas, Arbeloa-Ibero, and Quinn 2019). While Danelli and Brivio (2022) assumed a complete inverter replacement after 17 years, PV LCAs often assume 10% replacement of the inverter and transformer by weight every 10 years based on Mason et al. (2006), which Antonanzas, Arbeloa-Ibero, and Quinn (2019) found to be consistent with NREL operations and maintenance analysis (Walker 2018).

3.5 End-of-Life

Decommissioning. We assume diesel use for decommissioning is equivalent to the diesel use for installation per Antonanzas, Arbeloa-Ibero, and Quinn (2019).

Balance-of-system EOL. In the literature, BOS components are widely assumed to be processed for metal scrap (Ravikumar et al. 2016; Antonanzas, Arbeloa-Ibero, and Quinn 2019; Méndez et al. 2021; Bergesen et al. 2014; Jungbluth et al. 2012). We built an EOL inventories for BOS primarily based on Bergesen et al. (2014) for metal recovery (90% for steel, 79% for aluminum, 76% for copper). We also incorporated plastic and concrete disposal from Méndez et al. (2021). BOS EOL impacts are evaluated by comparing a cutoff approach and avoided burden approach in the final results.

Module EOL. As mentioned previously in Section 2.1, three EOL options for modules were considered because of uncertainty regarding which EOL protocols will be dominant in 30 years, at the end of the service life for a system installed in 2022. The three options include landfilling, partial recycling, and potential high-recovery recycling. Landfilling and partial recycling represent some current industry practices: PV modules are not considered hazardous waste in many U.S. states (Curtis et al. 2021a) and can therefore be landfilled, but are sometimes partially recycled. Impacts from each of these options are evaluated by comparing a cutoff approach to an avoided burden approach as described previously in Section 2.1.

1. **Landfilling.** The inventory for landfilling a PV module was sourced from Ravikumar et al. (2016). While this study primarily considers cadmium telluride modules, the landfilling inventory is technology-agnostic and can be applied to a generic module. This inventory includes the energy intensity of the landfill operation, transportation to the landfill, and electricity generated by the landfill.
2. **Partial recycling.** Current common recycling practices for PV modules are considered here as partial recycling, which primarily represent downcycling processes. The junction box is removed and sent to electronics recycling for copper recovery, the aluminum frame is removed and recycled, and the remaining module laminate is processed typically by a glass recycler to be recycled for an application with less stringent material purity requirements, such as optical road glass beads or fiberglass. The inventory for partial recycling methods was sourced from Stolz et al. (2017), who surveyed data of European glass recyclers who currently process PV module waste. It considers transportation, electricity usage, burning of plastics, and recovery of glass, copper, and aluminum.
3. **Hypothetical high-recovery recycling.** The high-recovery recycling option targets more component materials for higher-purity recovery, including silicon and silver. For this option, we consider an inventory for the Full Recovery End of Life PV (FRELP) process, which was piloted but never fully scaled up (Latunussa et al. 2016). This option represents a hypothetical high-purity recovery process that could be developed at scale by the time a contemporary PV system is decommissioned.

The full set of EOL scenarios are reported in Table 7. In this report, the cutoff approach assumes 100% of impacts are allocated to the PV system. This is likely a significant overestimate but is used to illustrate the maximum potential impact, particularly given the uncertainty around allocation occurring 30 years in the future.

Table 7. End-of-Life Scenario Definitions

EOL scenario	Decommissioning	BOS EOL	Module EOL
Landfill	Decommissioning	Scrap, cutoff approach	Landfill
Partial recycling, cutoff	Decommissioning	Scrap, cutoff approach	Partial recycling, cutoff approach
Hypothetical high-recovery recycling, cutoff	Decommissioning	Scrap, cutoff approach	Hypothetical high-recovery recycling, cutoff approach
Partial recycling, avoided burden	Decommissioning	Scrap, **avoided burden**	Partial recycling, **avoided burden**
Hypothetical high-recovery recycling, avoided burden	Decommissioning	Scrap, **avoided burden**	Hypothetical high-recovery recycling, **avoided burden**

4 Impact Assessment

The impacts reported in this section are shown both per kilowatt dc and kilowatt-hour for ease of comparisons with other studies. Units of kilowatt dc represent irradiance in standard test conditions, while results per kilowatt-hour are divided by the total kilowatt-hours of generation of the 100-MW_{dc} system over a 30-year service life in the three installation locations described in Section 2. Annual energy generation and 30-year generation totals are reported for each location in Appendix B, produced by the NREL System Advisor Model (NREL 2023).

4.1 Cumulative Energy Demand

The CED results are reported in Figure 7 per kW_{dc}, which reflects primary energy in $MJ_{oil\text{-}eq}$ from all energy resource types and is mainly used in the calculation of EPBT in this report. The range above each bar captures the range of EOL scenarios for each of the six main cases. End-of-life impacts are shown in gray with error bars, where the negative segments represent the avoided burden approach and the positive segments represent the cutoff approach. As described in Section 3.5, all EOL scenarios include decommissioning. However, landfill and "high-recovery, cutoff" include the BOS EOL cutoff approach, while the "partial recycling, AB" and "high recovery, AB" include the BOS EOL avoided burden (AB) approach.

Overall, the imported supply chains represent a greater range of CED than the domestic supply chains. The CED for the U.S. low-carbon region is higher than the CED for imports from a low-carbon region, due to the higher amount of nuclear in the U.S. grid mix, which results in low GHG emissions but a higher primary energy demand. Overall, CED per kW_{dc} varies by a factor of 1.33 depending on supply chain region and end-of-life treatment. The contribution from the updated inverter inventory is about half of the 500kW inverter inventory available in ecoinvent 3.9 (when scaled for the same functional unit). The updated inverter CED represents an approximately 1:5 ratio compared to the transformer CED, but in total these two components represent less than 8% of CED impacts.

In Figure 8, CED results are also presented in $MJ_{oil\text{-}eq}$ per megajoule generated ($MJ_{UPV\text{-}generated}$) (converted from kWh) to directly illustrate the energy efficiency of the UPV system. To illustrate the feasible range of impacts, the high-carbon manufacturing regions are paired with the low-irradiance installation location (Seattle), while the low-carbon manufacturing regions are paired with the high-irradiance installation location (Phoenix). This illustrates that CED per kWh can vary by a factor of 1.6 or greater depending on the supply chain region, installation location, and EOL scenario. The high-carbon regions for both supply chains show ratios around 0.1, which demonstrates efficient use of primary energy resources; however, this assumes install in a low-irradiance region. The weighted average and low-carbon regions for both supply chains are even lower.

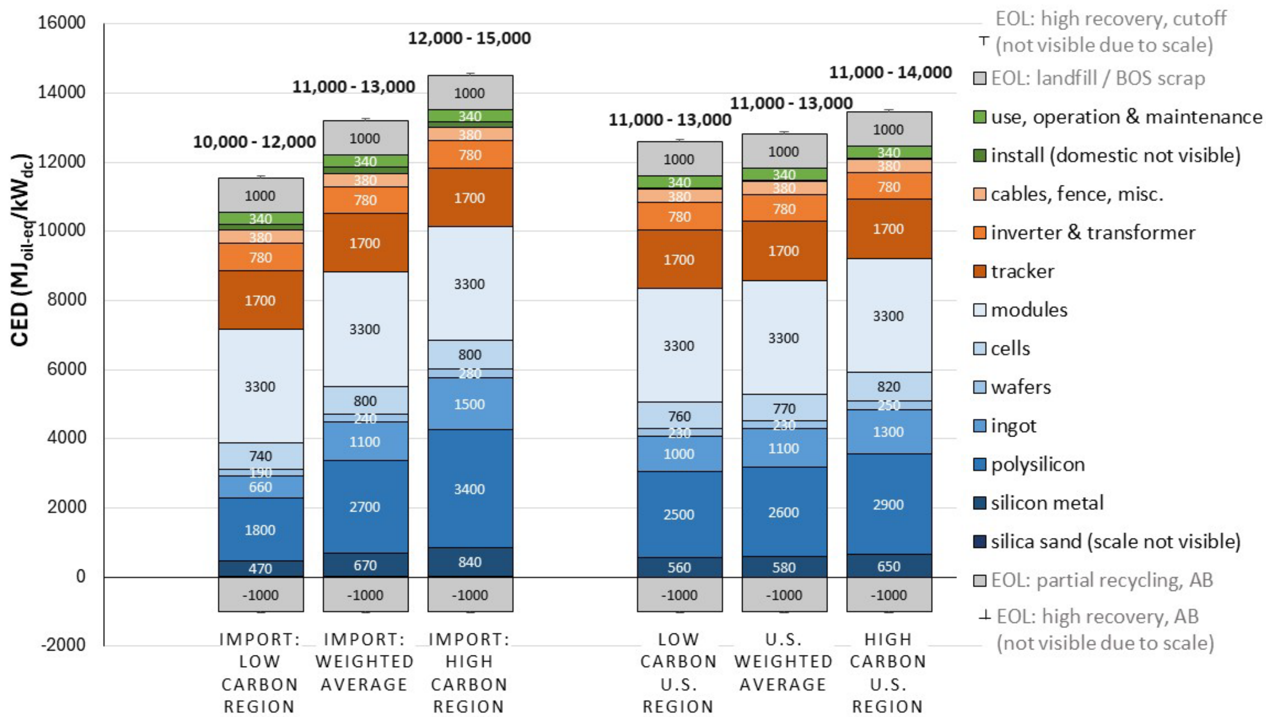

Figure 7. CED per kW_{dc} over the life cycle of a UPV system installed in the United States: 20.3% efficient monofacial PERC modules, single-axis tracker, 0.7% degradation rate, 30-year system life

We also present nr-CED per $MJ_{UPV\text{-}generated}$ (converted from kWh) in Appendix B, but these results do not differ significantly from the full CED impacts. In the high-carbon regions, these results are approximately the same because more than 90% of CED is from nonrenewable resources. While low-carbon regions typically have less than 90% of CED from nonrenewable resources, the discrepancy between CED and nr-CED is typically not on the order of significant digits evaluated in this work. Our values for PV CED in this work are approximately the same or lower than previous PV CED results in literature, but are still an order of magnitude lower than fossil-based energy generation technologies (Raugei and Leccisi 2016; Raugei et al. 2018).

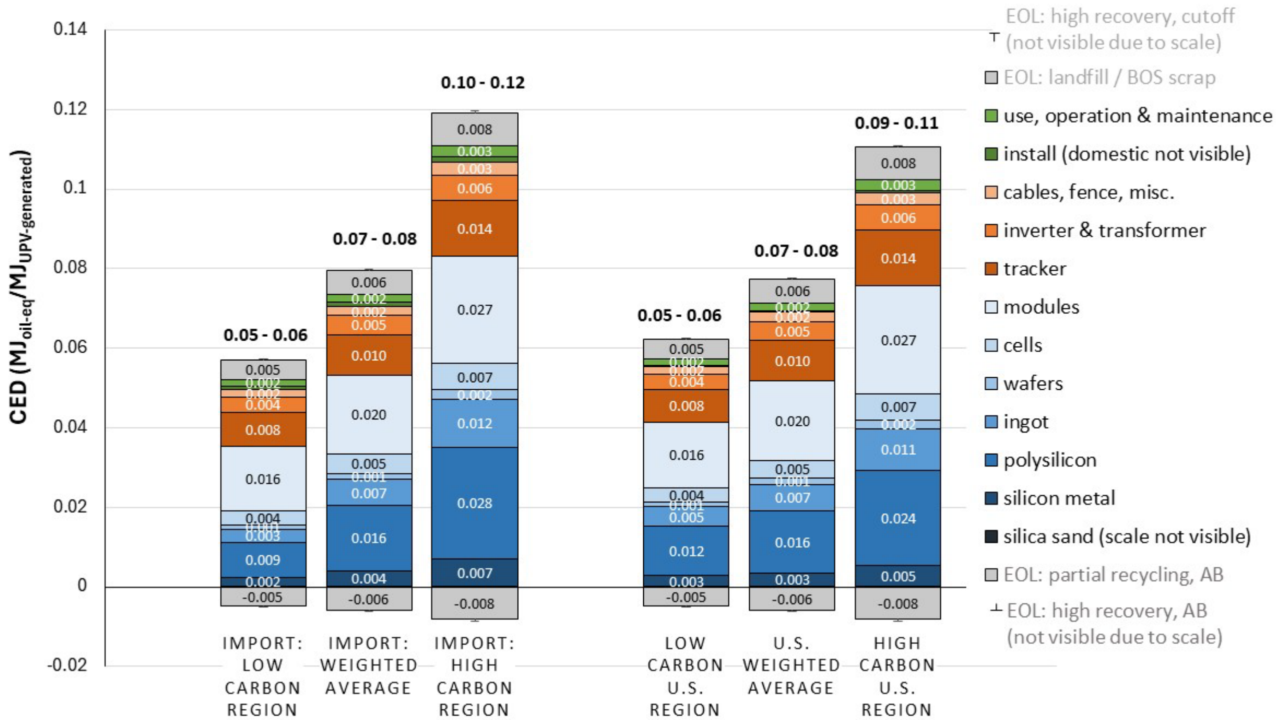

Figure 8. CED per megajoule generated by UPV systems installed in the United States: 20.3% efficient monofacial PERC modules, single-axis tracker, 0.7% degradation rate, 30-year system life.

Low-carbon cases installed in Phoenix, AZ; Weighted average cases installed in Fredonia, KS; High-carbon cases installed in Seattle, WA; annual energy generation reported in Appendix B.

4.2 Greenhouse Gas Emissions

Life cycle GHG emissions are reported in Figure 9 per kilowatt dc for ease of comparison with many LCAs, which often rely primarily on this functional unit. Again, the range above each bar reflects the multiple EOL scenarios (represented in the gray segments of the bar chart and the error bars), where the negative segments represent the avoided burden approach and the positive segments represent the cutoff approach.

Similar to CED impacts, the imported supply chains show a greater range of GHG emissions than the domestic supply chains. However, unlike the CED results, the U.S. low-carbon supply chain shows lower GHG impacts than the corresponding low-carbon imported supply chain, due to the lower-emission U.S. grid. Overall, GHG emissions per kW_{dc} can vary by a factor of 1.5 depending on supply chain region and end-of-life treatment. Again, the GHG emissions from the updated inverter inventory is about half of the 500-kW inverter inventory available in ecoinvent 3.9 (when scaled for the same functional unit). The updated inverter GHG emissions still represent a 1:3 ratio compared to the transformer GHG emissions; however, in total these two components represent less than 6% of lifetime system GHG emissions.

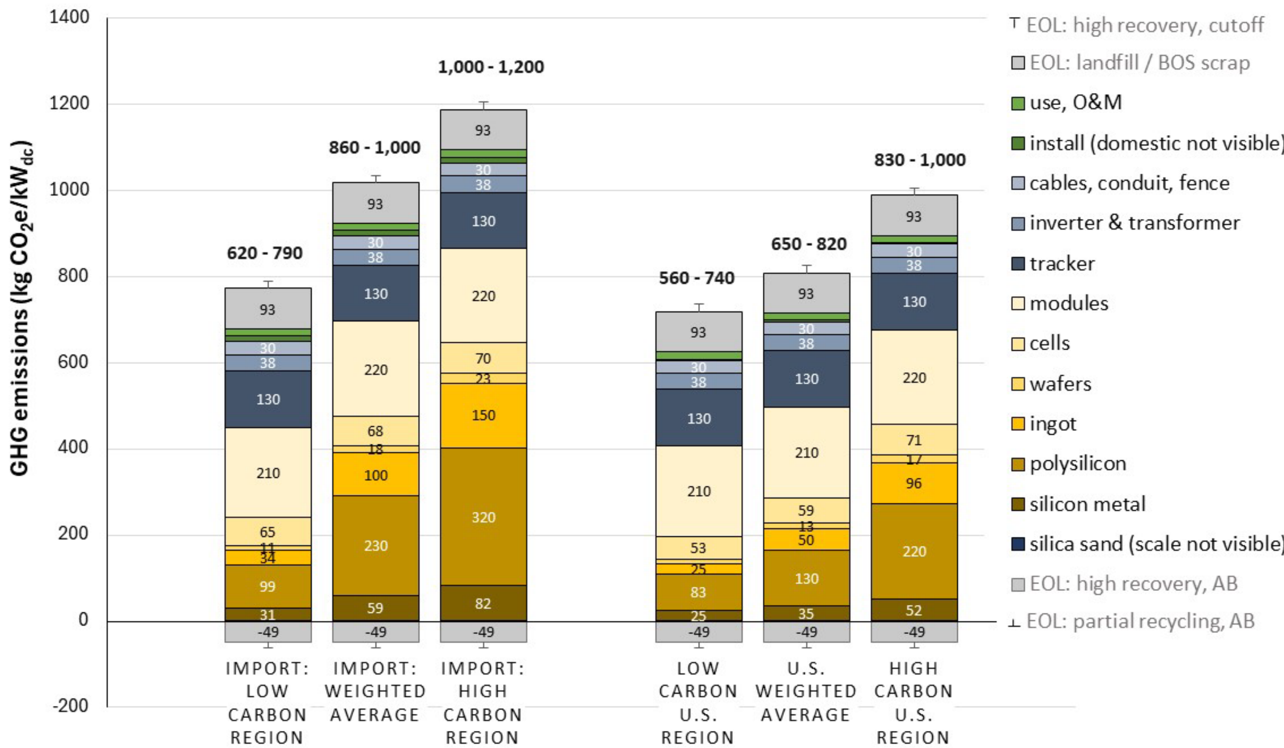

Figure 9. GHG emissions per kilowatt dc over the life cycle of a UPV system installed in the United States: 20.3% efficient monofacial PERC modules, single-axis tracker, 0.7% degradation rate, 30-year system life

Many LCAs in literature focus on PV module production only, so we first present a comparison to literature at the module level. Other than the ingot and wafer input discrepancy described in Section 3.2, the results are relatively comparable with the glass-backsheet module from Müller et al. (2021), though older data for an average China grid mix is used as well as the 2013 IPCC GWP factors. The glass-glass module modeled in Müller et al. (2021) has lower GHG emissions, which is exclusively due to the omission of an aluminum frame. GHG results are also in relatively good agreement with Anctil, Farina, and Yuan (2023), who considered the regional effects of manufacturing.

Furthermore, these GHG results span the range reported in the EPEAT ecolabel criteria for PV modules (Global Electronics Council 2023), which excludes installation, operation, and EOL phases. PV modules may only receive the low-carbon PV ecolabel if GHG emissions are below 630 kg CO_2e/kW, which means the average and low-carbon U.S. supply chain modules would comply, but only imports from a low-carbon region would comply. Furthermore, PV modules can receive an “ultra-low-carbon” ecolabel if module emissions are below 400 kg CO_2e/kW. Among the results within this report, only the low-carbon U.S. supply chain would comply.

When evaluating literature that considers the entire system, the GHG results per kilowatt are lower than what is reported in Antonanzas, Arbeloa-Ibero, and Quinn (2019), though much of the discrepancy can be explained by the improved module efficiency modeled in this report.

In Figure 10, GHG emission results are also shown per kWh. Again, to illustrate the feasible range of impacts, the high-carbon manufacturing regions are paired with the low-irradiance installation location (Seattle), and the low-carbon manufacturing regions are paired with the high-irradiance installation location (Phoenix). This illustrates that GHG per kWh can vary by a factor of 1.7 or greater depending on the supply chain region, installation location, and EOL scenario.

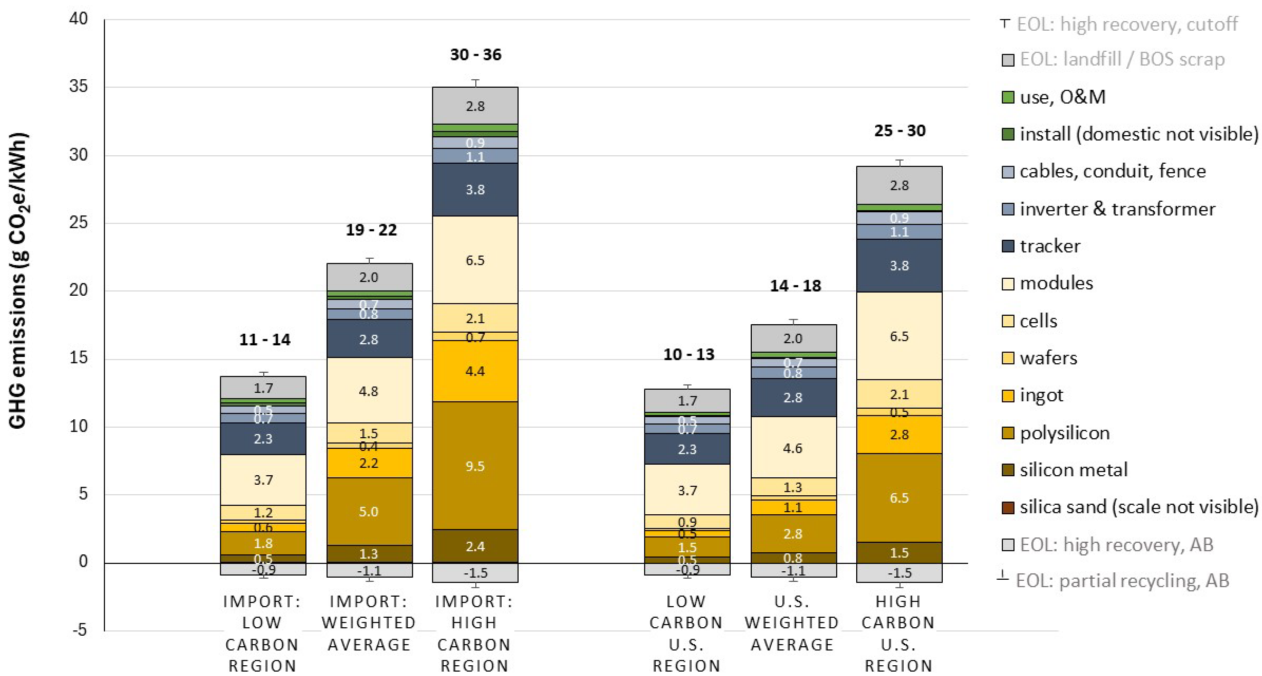

Figure 10. GHG emissions per kilowatt-hour for UPV systems installed in the United States: 20.3% efficient monofacial PERC modules, single-axis tracker, 0.7% degradation rate, 30-year system life.

Low-carbon cases installed in Phoenix, AZ; Weighted average cases installed in Fredonia, KS; High-carbon cases installed in Seattle, WA; annual energy generation reported in Appendix B.

Compared to the literature, the GHG results per kWh are relatively consistent. The results for a Chinese supply chain in Méndez et al. (2021) are roughly in agreement with the average imported supply chain above, and their Spain supply chain results approximate the average U.S. supply chain case. Furthermore, the results in this report (10–36 g CO_2e/kWh) are within or below the range documented in the NREL LCA harmonization study (NREL 2021) depicted in Figure 11, as well as recent updates from IEA-PVPS (Frischknecht 2021).

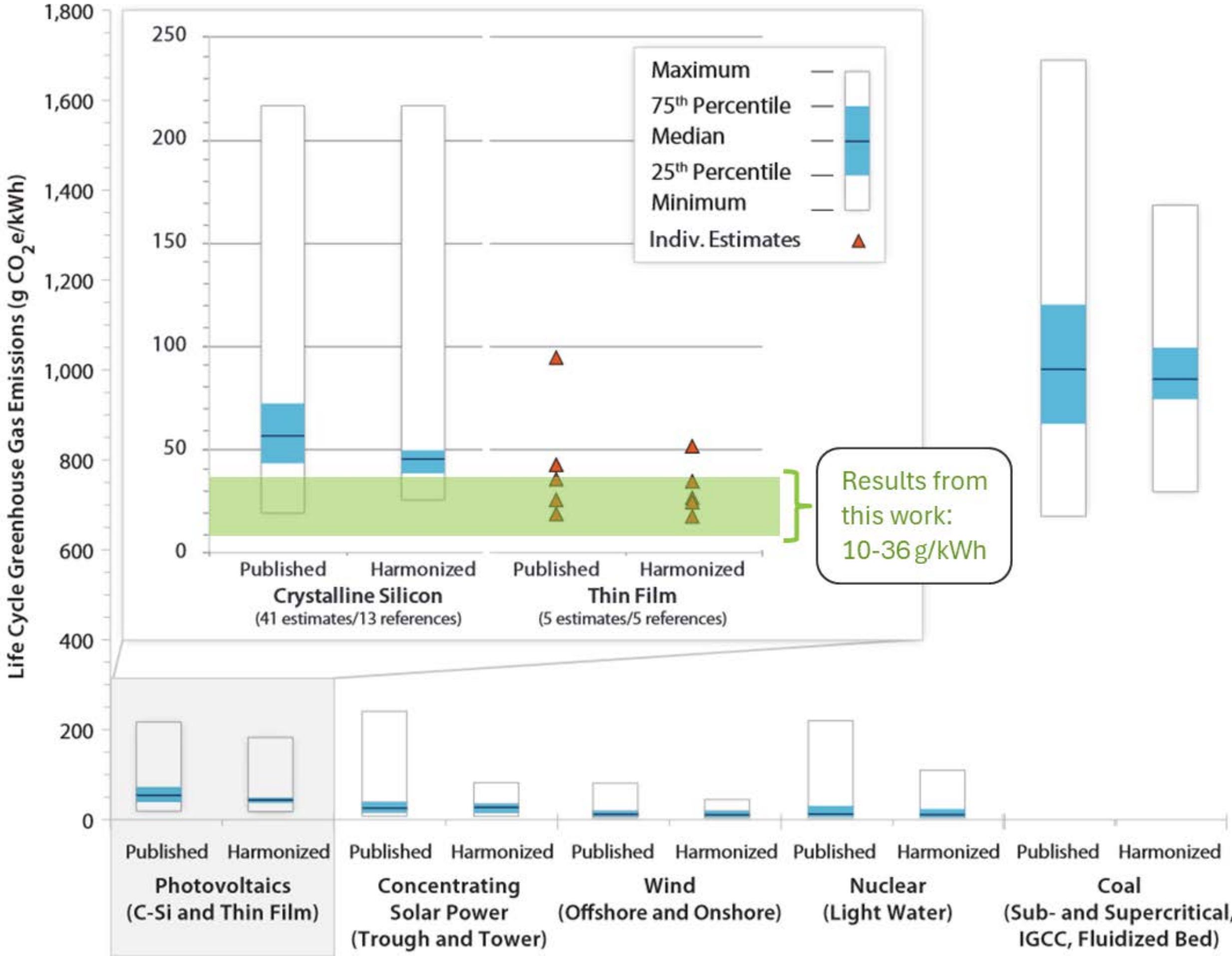

Figure 11. Comparison of as-published and harmonized life cycle greenhouse gas emission estimates for selected electricity generation technologies, reproduced from the NREL life cycle assessment harmonization study (NREL 2021)

5 Interpretation

As described in Section 2.4, EPBT and CPBT are estimated by:

- Plotting the full life cycle impacts (CED or GHG) of a 100-MW_{dc} UPV system
- Plotting cumulative energy generation (annually) or cumulative emissions avoided (annually)
- Identifying the points of intersection.

Results are shown in the following subsections for systems assumed to be installed during 2022 and begin the first year of operation in 2023. Not all cases are presented in the subsequent sections. Both EPBT and CPBT results present the benchmark weighted average imported supply chain (with avoided burden partial recycling) as the mid-case result, shown as a dashed line in the following figures. However, the highest- and lowest-impact cases from Section 4 are also displayed, which differ slightly for CED and GHG and are discussed below.

5.1 Energy Payback Time

To estimate EPBT, cumulative energy generation from a 100-MW_{dc} UPV system in Phoenix, Fredonia, and Seattle are plotted in Figure 12 based on the annual energy generation data reported in Appendix B and scaled by grid efficiency. The horizontal lines represent the cumulative energy demand for three cases in this report:

- Highest CED: imported module from high-carbon region with landfill EOL
- Middle CED: imported module weighted average, with avoided burden partial recycling
- Lowest CED: imported module from low-carbon region and avoided-burden high recovery recycling.

This illustrates that the range of EPBTs possible in the United States spans 0.5 to 1.2 years, depending on the supply chain and installation location. Clearly, the lowest EPBT is achieved by a low-carbon supply chain installed in a high-irradiance location (circle A), and the highest EPBT results from a high-carbon supply chain installed in a low-irradiance location (circle C). When considering the mid-case in an average-irradiance location, the benchmark EPBT in this report is 0.6 years (circle B). This is below the benchmark nonrenewable EPBT of 1.2 years reported for 20% efficient monocrystalline silicon modules from IEA-PVPS (Frischknecht 2021).

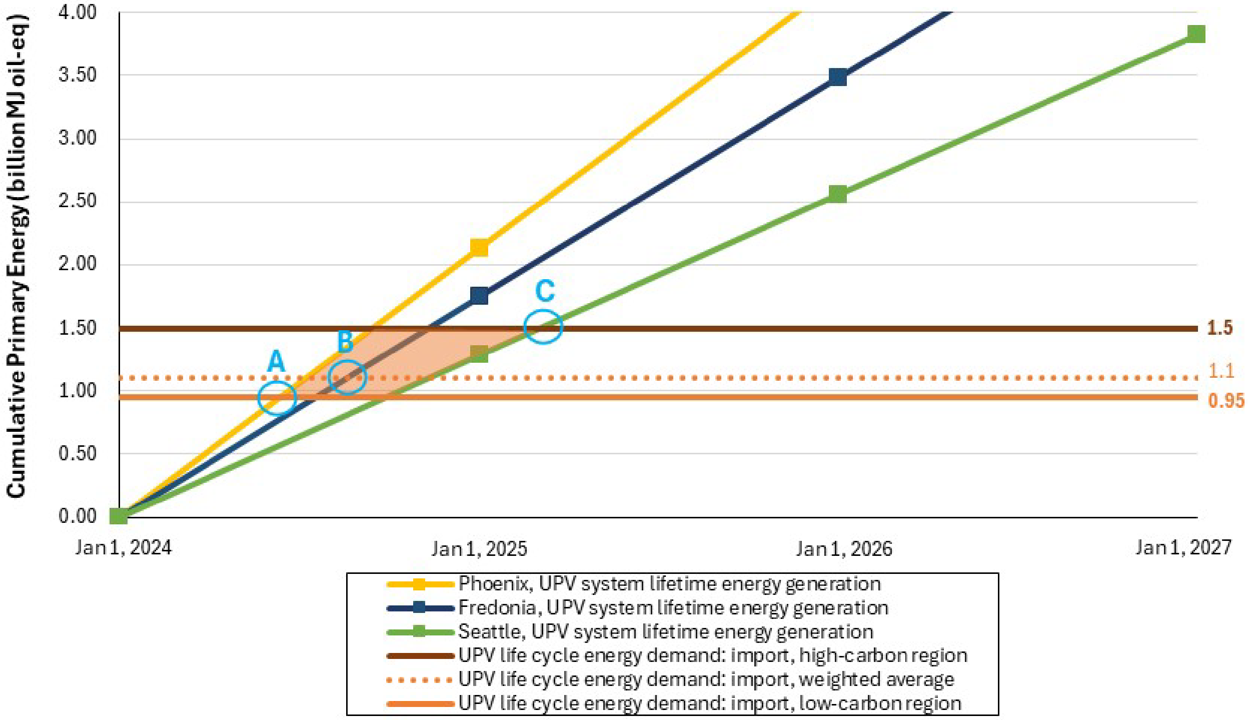

Figure 12. Energy payback time for 100-MW$_{dc}$ UPV system installed in the United States

(A) Low-carbon imported modules installed in Phoenix, AZ; (B) Weighted-average imported modules installed in Fredonia, KS; (C) High-carbon imported modules installed in Seattle, WA.

5.2 Carbon Payback Time

To estimate CPBT, cumulative emissions avoided by energy generated from a 100-MW$_{dc}$ UPV system in Phoenix, Fredonia, and Seattle are plotted in Figure 13. The data show significant curvature due to effects from both the system degradation rate as well as the changing grid mix associated with the respective Cambium scenarios. The horizontal lines represent the life cycle GHG emissions for the UPV system in three cases from this report:

- Highest GHG emissions: imported module from high-carbon regions, with landfill EOL
- Middle GHG emissions: weighted-average imported module, with avoided burden partial recycling
- Lowest GHG emissions: domestic module from a low-carbon region, and avoided burden high-recovery recycling.

Figure 13 illustrates that the range of CPBTs possible in the United States spans from 0.8 years (circle A) to almost 20 years (circle C, which falls outside the chart range for legibility), depending on the supply chain and installation location. The Seattle data in the CPBT chart are much lower than the other installation locations primarily due to the large amount of hydropower already contributing to the Seattle grid. However, for an average manufacturing supply chain, the CPBT is likely less than 14 years even when installed in a low-irradiance location with a low-emission grid. Clearly the lowest CPBT is achieved by a low-carbon supply chain installed in a high-irradiance location with a high-emission grid, and the highest CPBT is from a high-carbon supply chain installed in a low-irradiance location with a low-emission grid. When considering the mid-case installation location, the benchmark CPBT in this report is 2.1 years (circle B).

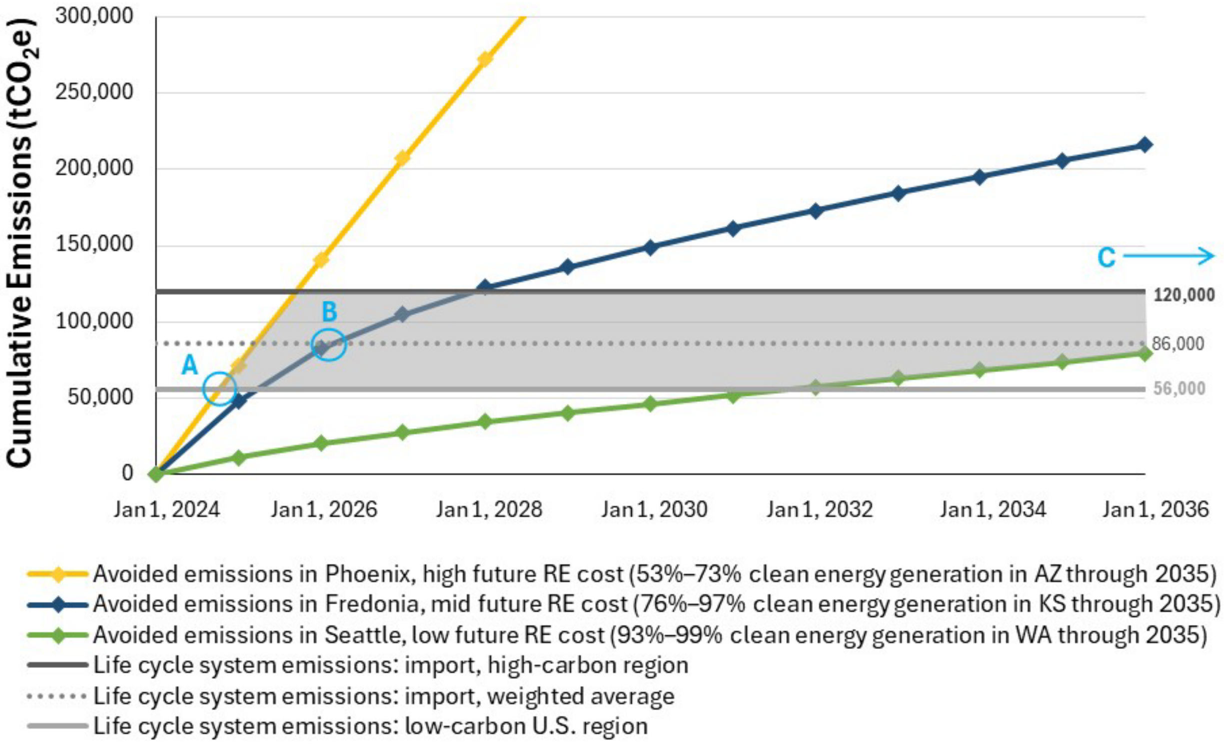

Figure 13. Carbon payback time for 100-MW_{dc} UPV system installed in the United States.

(A) Low-carbon domestic modules installed in Phoenix, AZ; (B) Weighted-average imported modules installed in Fredonia, KS; (C) High-carbon imported modules installed in Seattle, WA.

Due to the greater nonlinearity in emissions data, the graphical approach has a significant effect on the CPBT result. For the Kansas mid-case benchmark, the more common "average annual emissions" CPBT method produces a carbon payback time of 7 years, which is more than 3 times the value we estimate using the graphical method. While CPBT is not commonly assessed in PV LCA literature, most report within a range of 2–5 years, including for high-irradiance U.S. installation locations such as Phoenix (Kothari and Anctil 2022; Grant and Hicks 2020; Wang et al. 2020).

This underscores the importance of installation location effects on CPBT. The high-carbon supply chain easily achieves a CPBT of 2.1 years or less for both the high-irradiance/high-emission location (Phoenix) and the mid-irradiance/mid-emission location (Fredonia). However, the CPBT of a high-carbon imported supply chain exceeds 19 years in the low-irradiance/low-emission location (Seattle). We determined that the effects of the grid mix projection in this location were minimal: applying a high future renewable cost scenario for Seattle only reduced the CPBT of systems with high-carbon imported modules by 1 year. Conversely, applying a low future renewable cost for Phoenix increases the CPBT by 0.4 years – 1.0 year for the low-carbon and high-carbon supply chains, respectively.

5.3 Caveats

One of the challenges with using CPBT as a metric is that greenhouse gases emitted in the near term have a greater effect on climate change. The CPBT method in this work essentially assumes all emissions are equal as if they are occurring at the same time, even though they are emitted over the life cycle of the system.

Grid efficiency in this analysis was based on energy conversion of the state grid for the year 2019 in the respective locations. We also apply 2019 values for future years for this analysis. If grid efficiency continues to increase, following past trends (LLNL 2022), using 2019 values would underestimate EPBT (i.e., EPBT could be slower than the value shown). However, because the current EPBT values are small (<1.5 years), the effect of the underestimation is also expected to be minor. One can calculate the energy conversion factors for the future-state grid using Cambium grid mix data and the energy efficiency factors for various technologies (out of scope for this analysis).

Grid emission factors were modeled using Cambium and the NETL Grid Mix Explorer. Both models have their own set of limitations. Detailed discussion surrounding the limitation of the Cambium model can be found in Gagnon, Cowiestoll, and Schwarz (2023). While there is no single document describing the limitation of the Grid Mix Explorer, researchers can read through the life cycle assessment limitations for each individual technology linked in the tool (Skone 2020). NETL models the average emission rate of the grid, which may not capture short-run consequences of interventions, as compared to marginal emission rates. While Cambium does capture marginal emission rates, it focuses on fuel combustion and does not include total life cycle emissions when estimating marginal impacts. Further information on the impact of average emission rate versus marginal emissions rates can be found in Gagnon and Cole (2022).

6 Areas for Future Research

The PERC technology modeled here is the current dominant architecture within the silicon cell market as of 2022. However, industry expects that new technologies, including tunnel oxide passivated contact (TOPCon) and silicon heterojunction devices, are expected to gain market share in the coming decade (Fischer et al. 2023). Future inventories should reflect these new designs, the required cell processing energy, and higher energy yields. Similarly, applications within bifacial modules should also be considered.

Despite the completed technology shift from slurry cutting to diamond wire saw in 2018 (ITRPV Working Group 2019), many inventories in literature include outdated inputs for the sawing process, including glycol, and use approximate analogs for the diamond wire itself (e.g., chromium steel alloys). Diamond wires are created in at least two ways, including resin coated and electroplated diamonds. While wire sawing is typically a background process, an updated inventory would improve accuracy.

Current resolution into material and energy inputs for operation and maintenance processes are limited in literature. While the use phase of PV has not typically shown high impacts, a dedicated assessment could potentially reveal significant effects on LCA results if array cleaning or tracker component replacement is often necessary. Similarly, more exhaustive end-of-life inventories for BOS components may produce similar effects.

Inventories for PV recycling were taken from pre-2017 European data. While these inventories should be representative of current practices in the United States, modern country-specific data would be helpful. Additionally, PV recycling practices are rapidly evolving and will need to be monitored for future changes and improvements.

Additionally, future work would benefit from greater resolution into regional emissions across the different manufacturing processes. This could inform a decisional prospective LCA to optimize the locations for different segments of the supply chain. Dedicated power purchase agreements could be considered, particularly for the more energy-intensive processes.

Future studies that consider a domestic supply chain could evaluate domestic production of input components upstream of the foreground processes in this work. For example, the carbon benefits of U.S. aluminum production for PV applications has been studied recently by Gan et al. (2023).

Finally, the potential effects of short-run marginal displacement on CPBT should be examined, accounting for which energy technologies PV displaces seasonally or at a specific time-of-use. Furthermore, studies should also consider how it may change when conducting an LCA of a PV system paired with storage.

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Appendices A–C contain methodological or supplementary information that may aid in understanding the research presented in this report. This information is also provided to allow other readers or researchers to employ, modify, or critique this research effort.

Appendix A. Inventory Data

A.1 Data Quality & Limitations

Some qualitative descriptions of data quality and limitations are included in Section 2.2 and Section 3, however standardized methods exist for assessing the quality of data in life cycle inventories which can be semi-quantitative and used to inform uncertainty analysis in LCA data (Edelen & Ingwersen 2018). For example, data quality can be assessed at both the flow level and process level using a pedigree matrix, such as the data quality indicators defined by the U.S. Environmental Protection Agency (EPA) in (Edelen & Ingwersen 2016) or similar indicators from the ecoinvent database (Weidema et al. 2013). However, due to this work's significant reliance on inventories from literature which do not report these types of data quality assessments, a comprehensive semi-quantitative assessment of data quality in this work is not feasible. For this reason, we provide further qualitative discussion of data quality and limitations in this appendix.

Data Quality Goals. The data quality guidance from the EPA advises establishing data quality goals; particularly, temporal, geographic, technological, and completeness goals. As we described in Section 2.2, we limited our collection of inventory data to reflect technologies with the largest market share in 2022 (modern PERC modules, single-axis trackers, large central inverters, and system performance described in Section 2.1) and focused on inventory data published after 2018. These data collection parameters represent the temporal and technological data quality goals in this work, particularly for foreground processes. The geographic goals are primarily set at the national level (D) for the United States, China, Malaysia, Thailand, and Vietnam, though scenario analysis is performed at the regional level (E) for the United States and China to examine national variability in electricity mixes, and defined by electric grid regions. Finally, goals regarding data completeness are somewhat relative in that we primarily rely on expert review and feedback to assess an acceptable level of completeness in inventories for foreground processes.

Limitations. Regarding the temporal goals, relatively modern inventories were available for most foreground processes but insight into background processes is somewhat limited and the ecoinvent data quality indicators for these processes should be consulted. In particular, electricity mix data from 2020 was available for China and the United States, but only 2019 for Malaysia, Thailand, and Vietnam. This may affect the results significantly depending on the amount of recent change in local grid mixes. Regarding technological goals, again relatively modern inventories were available for the relevant technologies in the foreground processes but some background processes may be more dated. For the inverter inventory in particular, weight or part counts for complex components (i.e., inductors, capacitors) were estimated and the best approximate inventories in the ecoinvent 3.9 database were used; however, these ecoinvent inventories are based on much smaller components than those used in a 2.7-MW_{ac} inverter and likely introduce some inaccuracies regarding material and energy use due to differences in both the design and manufacturing processes. Additionally, meeting temporal and technological data quality goals for end-of-life processes were somewhat challenging due to the uncertainty around EOL protocols 30 years into the future. For this reason, data collection for EOL inventories was less strict in terms of literature publication years and current technological market share. Regarding geographical data quality goals, the geographic resolution in this study is primarily limited to national differences in electricity and transportation distances. With the exception of silica sand and silicon metal production, differences in PV manufacturing processes between different countries were not captured in the scope of this work. Therefore, if significant differences exist in U.S. manufacturing processes for polysilicon, wafers, ingots, cells, and modules compared to other countries, these aspects are not captured in this work. Finally, with respect to completeness goals, we relied on industry and expert review as well as comparison with other literature to achieve an acceptable level completeness for different foreground process inventories. Most foreground processes are significantly complex such that an exhaustive accounting of flows was not pursued. For example, some inventories include the equipment needed for process operation while others do not, which can depend on the amount of infrastructure required and its throughput.

A.2 Manufacturing

Table A1. Inventory for Silica Sand Production, From Heidari and Anctil (2022)

Output Flows	**Unit**	**Amount**	
Silica sand	t	9.25E+04	
Input Flows	**Unit**	**Amount**	**Provider (ecoinvent processes)** Rest of World (RoW), Global (GLO)
building, hall	m^2	4.84E+01	building construction, hall - RoW
conveyor belt	m	9.15E+00	conveyor belt production RoW
diesel	kg	3.16E+04	diesel production, petroleum refinery operation - RoW
electricity, medium voltage	kWh	2.62E+05	*Varies by case defined in Tables 5–6*
gravel/sand quarry infrastructure	Item(s)	4.57E-03	gravel/sand quarry construction | RoW
heat, district or industrial, other than natural gas	MJ	1.85E+07	heat production, heavy fuel oil, at industrial furnace 1MW | RoW
heavy fuel oil	kg	5.25E+03	heavy fuel oil production, petroleum refinery operation | RoW
industrial machine, heavy, unspecified	kg	1.08E+03	industrial machine production, heavy, unspecified | - RoW
lime, packed	kg	2.72E+03	lime production, milled, packed - RoW
lubricating oil	kg	1.18E+02	lubricating oil production - RoW
sand, quartz	t	1.00E+05	
steel, unalloyed	kg	1.25E+03	steel production, converter, unalloyed - RoW
synthetic rubber	kg	1.92E+02	synthetic rubber production - RoW
transport, freight, light commercial vehicle	t*km	1.49E+03	transport, freight, light commercial vehicle - RoW
transport, freight, lorry, unspecified	t*km	1.01E+04	market group for transport, freight, lorry, unspecified | GLO

Output Flows	Unit	Amount	
Water, process and cooling, unspecified natural origin	m^3	1.33E+05	gravel/sand quarry construction | RoW
Water, process, unspecified natural origin	m^3	9.71E+05	heat production, heavy fuel oil, at industrial furnace 1 MW - RoW

Table A2. Inventory for Silicon Metal Production: Inputs From Heidari and Anctil (2022), Infrastructure From Méndez et al. (2021), Electricity for Import Cases From Chen et al. (2017), Wastes From Frischknecht et al. (2020b)

Output Flows	Unit	Amount	
silicon, metallurgical grade	kg	1	
Input Flows	**Unit**	**Amount**	**Provider**
charcoal	kg	1.70E-01	market for charcoal | charcoal | Cutoff, U - GLO
coke	MJ	2.31E+01	market for coke | coke | Cutoff, U - GLO
electric arc furnace converter	Item(s)	1.00E-11	market for electric arc furnace converter | electric arc furnace converter | Cutoff, U - GLO
electricity, medium voltage	kWh	Import: 1.30E+01 Domestic: 1.10E+01	*Varies by case defined in Tables 5–6*
graphite	kg	1.00E-01	market for graphite | graphite | Cutoff, U - GLO
oxygen, liquid	kg	2.00E-02	market for oxygen, liquid | oxygen, liquid | Cutoff, U - RoW
petroleum coke	kg	5.00E-01	market for petroleum coke | petroleum coke | Cutoff, U - GLO
silica sand	kg	2.70E+00	Table A1.
transport, freight train	t*km	6.90E-02	market for transport, freight train | transport, freight train | Cutoff, U - US
transport, freight, lorry, unspecified	t*km	1.56E-01	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
wood chips, wet, measured as dry mass	kg	3.25E-03	market for wood chips, wet, measured as dry mass | wood chips, wet, measured as dry mass | Cutoff, U - RoW
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
antimony	kg	7.85E-09	elementary flows/emission to air/low population density
arsenic	kg	9.42E-09	elementary flows/emission to air/low population density
boron	kg	2.79E-07	elementary flows/emission to air/low population density
cadmium	kg	3.14E-10	elementary flows/emission to air/low population density
calcium	kg	7.75E-07	elementary flows/emission to air/low population density
carbon dioxide, biogenic	kg	1.61E+00	elementary flows/emission to air/low population density
carbon dioxide, fossil	kg	3.58E+00	elementary flows/emission to air/low population density
carbon monoxide, fossil	kg	1.38E-03	elementary flows/emission to air/low population density
carbon monoxide, land transformation	kg	6.20E-04	elementary flows/emission to air/low population density

Output Flows	Unit	Amount	
chlorine	kg	7.85E-08	elementary flows/emission to air/low population density
chromium III	kg	7.85E-09	elementary flows/emission to air/low population density
cyanide	kg	6.87E-06	elementary flows/emission to air/low population density
fluorine	kg	3.88E-08	elementary flows/emission to air/low population density
heat, waste	MJ	7.13E+01	elementary flows/emission to air/unspecified
hydrogen fluoride	kg	5.00E-04	elementary flows/emission to air/low population density
hydrogen sulfide	kg	5.00E-04	elementary flows/emission to air/low population density
iron	kg	3.88E-06	elementary flows/emission to air/low population density
lead	kg	3.44E-07	elementary flows/emission to air/low population density
mercury	kg	7.85E-09	elementary flows/emission to air/low population density
nitrogen oxides	kg	9.74E-03	elementary flows/emission to air/low population density
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	9.60E-05	elementary flows/emission to air/low population density
particulates, >10 μm	kg	7.75E-03	elementary flows/emission to air/low population density
potassium	kg	6.20E-05	elementary flows/emission to air/low population density
silicon	kg	7.51E-03	elementary flows/emission to air/low population density
slag from metallurgical grade silicon production	kg	2.50E-02	market for slag from metallurgical grade silicon production | slag from metallurgical grade silicon production | Cutoff, U - GLO
sodium	kg	7.75E-07	elementary flows/emission to air/low population density
sulfur dioxide	kg	1.22E-02	elementary flows/emission to air/low population density
tin	kg	7.85E-09	elementary flows/emission to air/low population density

Table A3. Inventory for Polysilicon Production: Inputs From Méndez et al. (2021), Heat and Electricity From Müller et al. (2021), Transportation From Frischknecht et al. (2020b)

Output Flows	Unit	Amount	
silicon, solar grade	kg	1	
Input Flows	**Unit**	**Amount**	**Provider**
chlorine, gaseous	kg	2.15E-01	market for chlorine, gaseous | chlorine, gaseous | Cutoff, U - RoW
electricity, high voltage	kWh	7.20E+01	*Varies by case defined in Tables 5–6*
graphite	kg	5.40E-03	market for graphite | graphite | Cutoff, U - GLO
heat, district or industrial, natural gas	MJ	7.00E+01	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - RoW
hydrogen, liquid	kg	5.36E-02	market for hydrogen, liquid | hydrogen, liquid | Cutoff, U - RoW
nitrogen, liquid	kg	1.29E+01	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW

Output Flows	Unit	Amount	
quicklime, milled, packed	kg	5.80E-01	market for quicklime, milled, packed | quicklime, milled, packed | Cutoff, U - RoW
silicon, metallurgical grade	kg	1.26E+00	Table A2
silicone factory	Item(s)	1.00E-11	market for silicone factory | silicone factory | Cutoff, U - GLO
sodium hydroxide, without water, in 50% solution state	kg	3.50E-01	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
transport, freight train	t*km	3.65E+00	market for transport, freight train | transport, freight train | Cutoff, U - US
transport, freight, lorry, unspecified	t*km	2.87E+00	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
AOX, adsorbable organic halogen as Cl	kg	1.26E-05	elementary flows/emission to water/surface water
BOD5, biological oxygen demand	kg	2.05E-04	elementary flows/emission to water/surface water
chloride	kg	3.60E-02	elementary flows/emission to water/surface water
COD, chemical oxygen demand	kg	2.02E-03	elementary flows/emission to water/surface water
copper, ion	kg	1.02E-07	elementary flows/emission to water/surface water
DOC, dissolved organic carbon	kg	9.10E-04	elementary flows/emission to water/surface water
heat, waste	MJ	3.96E+02	elementary flows/emission to air/unspecified
iron, ion	kg	5.61E-06	elementary flows/emission to water/surface water
nitrogen	kg	2.08E-04	elementary flows/emission to water/surface water
phosphate	kg	2.80E-06	elementary flows/emission to water/surface water
sodium, ion	kg	3.38E-02	elementary flows/emission to water/surface water
TOC, total organic carbon	kg	9.10E-04	elementary flows/emission to water/surface water
zinc, ion	kg	1.96E-06	elementary flows/emission to water/surface water

Table A4. Inventory for Czochralski Ingot Production: Inputs Corrected From Müller et al. (2021), Transportation and Waste Heat From Frischknecht et al. (2020b)

Output Flows	Unit	Amount	
silicon, single crystal, Czochralski process, photovoltaics	kg	1	
Input Flows	**Unit**	**Amount**	**Provider**
acetone, liquid	kg	4.90E-02	market for acetone, liquid | acetone, liquid | Cutoff, U - RoW
argon, liquid	kg	4.60E-02	market for argon, liquid | argon, liquid | Cutoff, U - RoW
ceramic tile	kg	6.20E-02	market for ceramic tile | ceramic tile | Cutoff, U - GLO
electricity, medium voltage	kWh	3.84E+01	*Varies by case defined in Tables 5–6*

Output Flows	Unit	Amount	
hydrochloric acid, without water, in 30% solution state	kg	4.38E-04	hydrochloric acid production, from the reaction of hydrogen with chlorine | hydrochloric acid, without water, in 30% solution state | Cutoff, U - RoW
hydrogen fluoride	kg	3.51E-03	market for hydrogen fluoride | hydrogen fluoride | Cutoff, U - RoW
lime, hydrated, packed	kg	2.20E-02	market for lime, hydrated, packed | lime, hydrated, packed | Cutoff, U - RoW
nitric acid, without water, in 50% solution state	kg	7.78E-03	market for nitric acid, without water, in 50% solution state | nitric acid, without water, in 50% solution state | Cutoff, U - RoW
silicon, solar grade	kg	1.03E+00	*Table A3*
silicone factory	Item(s)	5.00E-12	market for silicone factory | silicone factory | Cutoff, U - GLO
sodium hydroxide, without water, in 50% solution state	kg	4.78E-03	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
transport, freight train	t*km	1.41E+00	market for transport, freight train | transport, freight train | Cutoff, U - US
transport, freight, lorry, unspecified	t*km	1.13E+00	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
water, completely softened	kg	6.84E-02	market for water, completely softened | water, completely softened | Cutoff, U - US
Water, cooling, unspecified natural origin	m^3	2.33E+00	
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
BOD5, biological oxygen demand	kg	1.30E-01	elementary flows/emission to water/unspecified
COD, chemical oxygen demand	kg	1.30E-01	elementary flows/emission to water/unspecified
DOC, dissolved organic carbon	kg	4.05E-02	elementary flows/emission to water/unspecified
fluoride	kg	2.37E-03	elementary flows/emission to water/surface water
heat, waste	MJ	1.15E+02	elementary flows/emission to air/low population density
hydrocarbons, unspecified	kg	2.28E-02	elementary flows/emission to water/surface water
hydroxide	kg	7.42E-03	elementary flows/emission to water/surface water
nitrogen	kg	9.10E-03	elementary flows/emission to water/surface water
TOC, total organic carbon	kg	4.05E-02	elementary flows/emission to water/unspecified
waste, from silicon wafer production, inorganic	kg	1.00E-01	market for waste, from silicon wafer production, inorganic | waste, from silicon wafer production, inorganic | Cutoff, U - GLO
water	m^3	3.00E-01	elementary flows/emission to air/unspecified

Output Flows	Unit	Amount	
water	m^3	2.20E+00	elementary flows/emission to water/unspecified

Table A5. Inventory for Monocrystalline Silicon Wafer Production: Inputs Corrected From Müller et al. (2021), Waste Heat From Frischknecht et al. (2020b)

Output Flows	Unit	Amount	
single-Si wafer, photovoltaic	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
acrylic binder, with water, in 54% solution state	kg	2.00E-03	market for acrylic binder, with water, in 54% solution state | acrylic binder, with water, in 54% solution state | Cutoff, U - RoW
alkylbenzene sulfonate, linear, petrochemical	kg	3.40E-02	market for alkylbenzene sulfonate, linear, petrochemical | alkylbenzene sulfonate, linear, petrochemical | Cutoff, U - GLO
brass	kg	7.45E-03	market for brass | brass | Cutoff, U - RoW
citric acid	kg	1.87E-01	market for citric acid | citric acid | Cutoff, U - GLO
electricity, medium voltage	kWh	2.35E+00	*Varies by case defined in Tables 5–6*
glass wool mat	kg	1.06E-02	market for glass wool mat | glass wool mat | Cutoff, U - GLO
heat, district or industrial, natural gas	MJ	1.80E+00	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - RoW
hydrogen peroxide, without water, in 50% solution state	kg	2.53E-02	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, U - RoW
potassium hydroxide	kg	3.81E-03	market for potassium hydroxide | potassium hydroxide | Cutoff, U - GLO
silicon, single crystal, Czochralski process, photovoltaics	kg	5.95E-01	*Table A4*
sodium hydroxide, without water, in 50% solution state	kg	1.50E-02	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
steel, low-alloyed, hot rolled	kg	8.96E-04	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, U - GLO
wafer factory	Item(s)	2.00E-06	market for wafer factory | wafer factory | Cutoff, U - GLO
water, completely softened	kg	2.17E+01	market for water, completely softened | water, completely softened | Cutoff, U - US
wire drawing, steel	kg	8.96E-04	market for wire drawing, steel | wire drawing, steel | Cutoff, U - GLO
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
AOX, adsorbable organic halogen as Cl	kg	5.01E-04	elementary flows/emission to water/surface water
BOD5, biological oxygen demand	kg	2.96E-02	elementary flows/emission to water/surface water
COD, chemical oxygen demand	kg	2.96E-02	elementary flows/emission to water/surface water

Output Flows	Unit	Amount	
copper, ion	kg	6.05E-05	elementary flows/emission to water/surface water
DOC, dissolved organic carbon	kg	1.11E-02	elementary flows/emission to water/surface water
heat, waste	MJ	8.00E+00	elementary flows/emission to air/low population density
nitrogen	kg	9.94E-03	elementary flows/emission to water/surface water
TOC, total organic carbon	kg	1.11E-02	elementary flows/emission to water/surface water
waste, from silicon wafer production	kg	2.00E-02	market for waste, from silicon wafer production | waste, from silicon wafer production | Cutoff, U - GLO
water	m^3	9.75E-03	elementary flows/emission to air/unspecified
water	m^3	5.53E-02	elementary flows/emission to water/unspecified

Table A6. Inventory for Trimethylaluminum Production: Updated From Müller et al. (2021)

Output Flows	Unit	Amount	
Trimethylaluminum, purified	kg	18	
Input Flows	**Unit**	**Amount**	**Provider**
aluminium chloride	kg	1.34E+00	aluminium chloride production | aluminium chloride | Cutoff, U - GLO
aluminium, wrought alloy	kg	2.16E+01	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
electricity, medium voltage	kWh	5.57E+00	*Varies by case defined in Tables 5 – 6*
helium	kg	1.20E-01	market for helium | helium | Cutoff, U - GLO
methylchloride	kg	6.09E+01	market for methylchloride | methylchloride | Cutoff, U - RoW
nitrogen, liquid	kg	8.25E-01	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW
paraffin	kg	1.53E-01	market for paraffin | paraffin | Cutoff, U - GLO
sodium	kg	3.30E+01	market for sodium | sodium | Cutoff, U - GLO
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
fly ash and scrubber sludge	kg	3.80E+00	treatment of fly ash and scrubber sludge, hazardous waste incineration | fly ash and scrubber sludge | Cutoff, U - RoW
hazardous waste, for incineration	kg	1.07E+02	treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, U - RoW

Table A7. Inventory for PERC Cell Production: Inputs From Müller et al. (2021), Transportation and Waste Heat From Frischknecht et al. (2020b), Silver Emission From Danelli et al. (In Review)

Output Flows	Unit	Amount	
photovoltaic cell, single-Si wafer	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
ammonia, anhydrous, liquid	kg	1.65E-02	market for ammonia, anhydrous, liquid | ammonia, anhydrous, liquid | Cutoff, U - RoW
calcium chloride	kg	2.07E-02	market for calcium chloride | calcium chloride | Cutoff, U - RoW
electricity, medium voltage	kWh	6.03E+00	*Varies by case defined in Tables 5–6*
heat, district or industrial, natural gas	MJ	3.55E+00	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - RoW
hydrochloric acid, without water, in 30% solution state	kg	6.81E-02	market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | Cutoff, U - RoW
hydrogen fluoride	kg	7.47E-02	market for hydrogen fluoride | hydrogen fluoride | Cutoff, U - RoW
metallization paste, back side	kg	1.02E-03	Müller et al. 2021
metallization paste, back side, aluminium	kg	9.01E-03	market for metallization paste, back side, aluminium | metallization paste, back side, aluminium | Cutoff, U - RoW
metallization paste, front side	kg	3.48E-03	market for metallization paste, front side | metallization paste, front side | Cutoff, U - RoW
nitric acid, without water, in 50% solution state	kg	8.22E-02	market for nitric acid, without water, in 50% solution state | nitric acid, without water, in 50% solution state | Cutoff, U - RoW
nitrogen, liquid	kg	2.62E+00	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW
nitrous oxide	kg	7.66E-03	market for nitrous oxide | nitrous oxide | Cutoff, U - GLO
oxygen, liquid	kg	3.34E-01	market for oxygen, liquid | oxygen, liquid | Cutoff, U - RoW
phosphorus oxychloride	kg	1.82E-04	market for phosphorus oxychloride | phosphorus oxychloride | Cutoff, U - RoW
photovoltaic cell factory	Item(s)	4.00E-07	market for photovoltaic cell factory | photovoltaic cell factory | Cutoff, U - GLO
potassium hydroxide	kg	1.51E-01	market for potassium hydroxide | potassium hydroxide | Cutoff, U - GLO
propane	kg	4.14E-02	market for propane | propane | Cutoff, U - GLO
silicon tetrahydride	kg	2.83E-03	market for silicon tetrahydride | silicon tetrahydride | Cutoff, U - GLO
single-Si wafer, photovoltaic	m^2	1.02E+00	*Table A5*
solvent, organic	kg	1.23E-02	market for solvent, organic | solvent, organic | Cutoff, U - GLO

Output Flows	Unit	Amount	
sulfuric acid	kg	2.06E-02	sulfuric acid production | sulfuric acid | Cutoff, U - RoW
transport, freight train	t*km	1.52E+00	market for transport, freight train | transport, freight train | Cutoff, U - RoW
transport, freight, lorry, unspecified	t*km	2.74E-01	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
transport, freight, sea, container ship	t*km	Import cases only: 1.57E+00	transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO
trimethylaluminum	kg	2.88E-04	*Table A6*
water, completely softened	kg	2.32E+01	market for water, completely softened | water, completely softened | Cutoff, U - RoW
Water, cooling, unspecified natural origin	m^3	2.31E-01	
water, deionised	kg	3.94E+01	water production, deionised | water, deionised | Cutoff, U - RoW
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
aluminium	kg	7.73E-04	elementary flows/emission to air/high population density
ethane, hexafluoro-, HFC-116	kg	1.19E-04	elementary flows/emission to air/high population density
heat, waste	MJ	5.18E+01	elementary flows/emission to air/low population density
hydrogen chloride	kg	2.66E-04	elementary flows/emission to air/high population density
hydrogen fluoride	kg	4.85E-06	elementary flows/emission to air/high population density
lead	kg	3.48E-07	elementary flows/emission to air/high population density
methane, tetrafluoro-, R-14	kg	2.48E-04	elementary flows/emission to air/high population density
nitrogen oxides	kg	5.00E-05	elementary flows/emission to air/high population density
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1.94E-01	elementary flows/emission to air/high population density
particulates, <2.5 µm	kg	2.66E-03	elementary flows/emission to air/high population density
silicon	kg	7.27E-05	elementary flows/emission to air/high population density
silver	kg	6.60E-06	elementary flows/emission to air/low population density
waste, from silicon wafer production, inorganic	kg	6.41E-03	market for waste, from silicon wafer production, inorganic | waste, from silicon wafer production, inorganic | Cutoff, U - GLO
wastewater from PV cell production	m^3	1.32E-02	market for wastewater from PV cell production | wastewater from PV cell production | Cutoff, U - RoW
water	m^3	1.68E-02	elementary flows/emission to air/unspecified

Output Flows	Unit	Amount	
water	m^3	2.77E-01	elementary flows/emission to water/unspecified

Table A8. Inventory for PERC Module Production: Inputs From Müller et al. (2021), Transportation From Frischknecht et al. (2020b), Wafer Waste Output From Danelli et al. (In Review)

Output Flows	Unit	Amount	
photovoltaic panel	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
adipic acid	kg	3.69E-04	market for adipic acid | adipic acid | Cutoff, U - GLO
aluminium alloy, AlMg3	kg	1.51E+00	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
copper, cathode	kg	1.48E-01	market for copper, cathode | copper, cathode | Cutoff, U - GLO
corrugated board box	kg	7.63E-01	market for corrugated board box | corrugated board box | Cutoff, U - RoW
diode, auxilliaries and energy use	kg	2.81E-03	diode production, auxilliaries and energy use | diode, auxilliaries and energy use | Cutoff, U - GLO
electricity, medium voltage	kWh	3.32E+00	*Varies by case defined in Tables 5–6*
ethylvinylacetate, foil	kg	7.93E-01	market for ethylvinylacetate, foil | ethylvinylacetate, foil | Cutoff, U - GLO
EUR-flat pallet	Item(s)	5.00E-02	EUR-flat pallet production | EUR-flat pallet | Cutoff, U - RoW
glass fibre reinforced plastic, polyamide, injection moulded	kg	1.88E-01	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
lead	kg	1.08E-02	market for lead | lead | Cutoff, U - GLO
lubricating oil	kg	1.61E-03	market for lubricating oil | lubricating oil | Cutoff, U - RoW
metal working, average for aluminium product manufacturing	kg	1.51E+00	market for metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | Cutoff, U - GLO
packaging film, low density polyethylene	kg	4.01E-02	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
photovoltaic cell, single-Si wafer	m^2	9.00E-01	*Table A7*
photovoltaic panel factory	Item(s)	4.00E-06	market for photovoltaic panel factory | photovoltaic panel factory | Cutoff, U - GLO
polyethylene terephthalate, granulate, amorphous	kg	2.81E-01	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO
polyethylene, high density, granulate	kg	2.42E-02	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
polyethylene, low density, granulate	kg	5.48E-02	market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO

Output Flows	Unit	Amount	
polyvinylfluoride, film	kg	4.51E-02	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
silicone product	kg	1.44E-01	market for silicone product | silicone product | Cutoff, U - RoW
solar glass, low-iron	kg	8.00E+00	market for solar glass, low-iron | solar glass, low-iron | Cutoff, U - GLO
tempering, flat glass	kg	8.00E+00	market for tempering, flat glass | tempering, flat glass | Cutoff, U - GLO
tin	kg	1.04E-02	market for tin | tin | Cutoff, U - GLO
transport, freight train	t*km	1.66E+01	market for transport, freight train | transport, freight train | Cutoff, U - RoW
transport, freight, lorry, unspecified	t*km	2.99E+00	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
Water, cooling, unspecified natural origin	m^3	7.16E-02	
wire drawing, copper	kg	1.48E-01	market for wire drawing, copper | wire drawing, copper | Cutoff, U - GLO
Waste Flows	**Unit**	**Amount**	**Waste Treatment**
carbon dioxide, fossil	kg	2.18E-02	elementary flows/emission to air/low population density
heat, waste	MJ	1.34E+01	elementary flows/emission to air/low population density
municipal solid waste	kg	9.34E-02	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	8.06E-03	elementary flows/emission to air/high population density
waste mineral oil	kg	1.61E-03	market for waste mineral oil | waste mineral oil | Cutoff, U – RoW
waste plastic, mixture	kg	2.48E-02	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - RoW
waste polyvinylfluoride	kg	9.02E-04	market for waste polyvinylfluoride | waste polyvinylfluoride | Cutoff, U - RoW
waste, from silicon wafer production	kg	3.52E-03	market for waste, from silicon wafer production | waste, from silicon wafer production | Cutoff, U – GLO
water	kg	2.79E-02	elementary flows/emission to air/unspecified

Table A9. Inventory for Single-Axis Tracker: Inputs From Antonanzas, Arbeloa-Ibero, and Quinn (2019)

Output Flows	Unit	Amount	
1-axis tracker (per module area)	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**

Output Flows	Unit	Amount	
aluminium, wrought alloy	kg	8.36E-02	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
battery cell, Li-ion, LFP	kg	4.60E-03	market for battery cell, Li-ion, LFP | battery cell, Li-ion, LFP | Cutoff, U - GLO
corrugated board box	kg	8.58E-02	market for corrugated board box | corrugated board box | Cutoff, U - US
electric motor, vehicle	kg	5.65E-02	market for electric motor, vehicle | electric motor, vehicle | Cutoff, U - GLO
photovoltaic panel, single-Si wafer	m^2	5.00E-03	module assembly VN-MY - RoW
polystyrene, high impact	kg	7.97E-04	market for polystyrene, high impact | polystyrene, high impact | Cutoff, U - GLO
section bar extrusion, aluminium	kg	8.36E-02	market for section bar extrusion, aluminium | section bar extrusion, aluminium | Cutoff, U - GLO
section bar rolling, steel	kg	9.45E+00	market for section bar rolling, steel | section bar rolling, steel | Cutoff, U - GLO
section bar rolling, steel	kg	8.36E-02	market for section bar rolling, steel | section bar rolling, steel | Cutoff, U - GLO
steel, chromium steel 18/8	kg	8.36E-02	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
steel, low-alloyed, hot rolled	kg	9.45E+00	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, U - GLO

Table A10. Inventory for Inverter: Inputs Estimated From Empirical Data and 500-kW Inverter Inventory From Jungbluth et al. (2012)

Output Flows	Unit	Amount	
2.7 MW_{ac} inverter	Items	1	
Input Flows	**Unit**	**Amount**	**Provider**
aluminium, wrought alloy	kg	80	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
cable, network cable, category 5, without plugs	m	940	market for cable, network cable, category 5, without plugs | cable, network cable, category 5, without plugs | Cutoff, U - GLO
cable, three-conductor cable	m	61	market for cable, three-conductor cable | cable, three-conductor cable | Cutoff, U - GLO
capacitor, electrolyte type, >2 cm height	kg	5	market for capacitor, electrolyte type, > 2cm height | capacitor, electrolyte type, > 2cm height | Cutoff, U - GLO
capacitor, film type, for through-hole mounting	kg	50	market for capacitor, film type, for through-hole mounting | capacitor, film type, for through-hole mounting | Cutoff, U - GLO
concrete slab	m^3	1.1	concrete slab - RoW
copper, cathode	kg	430	market for copper, cathode | copper, cathode | Cutoff, U - GLO
glass fibre reinforced plastic, polyamide, injection moulded	kg	30	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO

Output Flows	Unit	Amount	
inductor, ring core choke type	kg	650	market for inductor, ring core choke type | inductor, ring core choke type | Cutoff, U - GLO
integrated circuit, logic type	kg	0.2	market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO
lubricating oil	kg	1	market for lubricating oil | lubricating oil | Cutoff, U - RoW
printed wiring board, through-hole mounted, unspecified, Pb free	kg	3	market for printed wiring board, through-hole mounted, unspecified, Pb free | printed wiring board, through-hole mounted, unspecified, Pb free | Cutoff, U - GLO
reinforcing steel	kg	1200	market for reinforcing steel | reinforcing steel | Cutoff, U - GLO
transformer, high voltage use	kg	100	market for transformer, high voltage use | transformer, high voltage use | Cutoff, U - GLO
transistor, wired, big size, through-hole mounting	kg	0.3	market for transistor, wired, big size, through-hole mounting | transistor, wired, big size, through-hole mounting | Cutoff, U - GLO
fan, for power supply unit, desktop computer	kg	0.2	market for fan, for power supply unit, desktop computer | fan, for power supply unit, desktop computer | Cutoff, U - GLO

Table A11. Inventory for Transformer: Inputs From Antonanzas, Arbeloa-Ibero, and Quinn (2019) With Concrete Quantity Updated

Output Flows	Unit	Amount	
2.7 MW_{ac} transformer	items	1	
Input Flows	**Unit**	**Amount**	**Provider**
concrete slab	m^3	1.10E+00	concrete slab | ROW
copper, cathode	kg	5.80E+03	market for copper, cathode | copper, cathode | Cutoff, U - GLO
epoxy resin, liquid	kg	1.05E+03	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RoW
ferrite	kg	2.36E+04	market for ferrite | ferrite | Cutoff, U - GLO
injection moulding	kg	1.05E+03	market for injection moulding | injection moulding | Cutoff, U - GLO
lubricating oil	kg	2.10E+04	market for lubricating oil | lubricating oil | Cutoff, U - RoW
reinforcing steel	kg	2.00E+03	market for reinforcing steel | reinforcing steel | Cutoff, U - GLO
wire drawing, copper	kg	5.80E+03	market for wire drawing, copper | wire drawing, copper | Cutoff, U - GLO

Table A12. Inventory for Cables, Conduit, Other Electrical Balance of System: Inputs From Méndez et al. (2021)

Output Flows	Unit	Amount	
electrical balance-of-system (per module area)	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
aluminium, wrought alloy	kg	0.4	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
epoxy resin, liquid	kg	4.9E-05	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RoW
nylon 6	kg	6.4E-03	market for nylon 6 | nylon 6 | Cutoff, U - RoW
polycarbonate	kg	6.1E-05	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyvinylchloride, bulk polymerised	kg	0.11	market for polyvinylchloride, bulk polymerised | polyvinylchloride, bulk polymerised | Cutoff, U - GLO
wire drawing, copper	kg	0.4	market for wire drawing, copper | wire drawing, copper | Cutoff, U - GLO

Table A13. Inventory for Fence: Inputs From Antonanzas, Arbeloa-Ibero, and Quinn (2019)

Output Flows	Unit	Amount	
fence (per module area)	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
concrete, 25MPa	m^3	2.9E-05	market for concrete, 25MPa | concrete, 25MPa | Cutoff, U - RoW
section bar rolling, steel	kg	4.6E-02	market for section bar rolling, steel | section bar rolling, steel | Cutoff, U - GLO
steel, low-alloyed	kg	9.9E-02	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
wire drawing, steel	kg	5.3E-02	market for wire drawing, steel | wire drawing, steel | Cutoff, U - GLO
zinc coat, coils	m^2	3.3E-03	market for zinc coat, coils | zinc coat, coils | Cutoff, U - GLO

A.3 Installation

Table A14. Inventory for Installation: Diesel From Antonanzas, Arbeloa-Ibero, and Quinn (2019), Transport Estimated From Frischknecht et al. (2020b)

Output Flows	Unit	Amount	
Installed UPV system (per module area)	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
1-axis tracker (per module area)	m^2	1	Table A9
diesel, burned in building machine	MJ	2.6	market for diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO

Output Flows	Unit	Amount	
2.7 MW_{ac} inverter	Item(s)	4.30E-05	Table A10
Occupation, unspecified, natural (non-use)	m^2*a	3	
photovoltaic panel	m^2	1	Table A8
2.7 MW_{ac} transformer	Item(s)	4.30E-05	Table A11
transport, freight train	t*km	2.2	market for transport, freight train | transport, freight train | Cutoff, U - RoW
transport, freight train	t*km	2	market for transport, freight train | transport, freight train | Cutoff, U - RoW
transport, freight, lorry, unspecified	t*km	3.3E-03	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
transport, freight, lorry, unspecified	t*km	0.51	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
transport, freight, lorry, unspecified	t*km	0.55	market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO
transport, freight, sea, container ship	t*km	Import cases only: 201	transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO
electrical balance of system (per module area)	m^2	1	Table A12
fence (per module area)	m^2	1	Table A13

A.4 Use, Operations and Maintenance

Table A15. Inventory for Operations and Maintenance: Petrol Use From Sinha and de Wild-Scholten (2012), Actuator Use From Danelli and Brivio (2022), Inverter and Transformer Replacement From Mason et al. (2006), Panel Replacement From Klise, Lavrova, and Gooding (2018)

Output Flows	Unit	Amount	
30 years operation and maintenance (per module area)	m^2	1	
Input Flows	**Unit**	**Amount**	**Provider**
electric motor, vehicle	kg	1.70E-02	market for electric motor, vehicle | electric motor, vehicle | Cutoff, U - GLO
2.7 MW_{ac} inverter	Item(s)	1.30E-05	Table A10
petrol, low-sulfur	kg	5.50E-02	petrol production, low-sulfur | petrol, low-sulfur | Cutoff, U - RoW
photovoltaic panel	m^2	1.5E-02	Table A8
2.7 MW_{ac} transformer	Item(s)	1.30E-05	Table A11

A.5 End of Life

Table A16. Inventory for Decommissioning, Diesel Use From Antonanzas, Arbeloa-Ibero, and Quinn (2019)

Output Flows	Unit	Amount		
decommissioned UPV system (per module area)	m^2	1		
Input Flows	**Unit**	**Amount**		**Provider**
diesel, burned in building machine	MJ	2.6		market for diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO
installed UPV system (per module area)	m^2	1		Table A14.
Waste Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
PV module EOL	kg	10.9		Tables A18-A20
2.6 MW_{ac} transformer EOL	Item(s)	4.3E-05		Table A21
electrical balance of system EOL (per module area)	m^2	1		Table A22
1-axis tracker EOL (per module area)	m^2	1		Table A23
2.6 MW_{ac} inverter EOL	Item(s)	4.3E-05		Table A24

Table A17. Inventory for Landfilling PV Modules, From Ravikumar et al. (2016)

Input Flows	Unit	Amount	Avoid	Provider
electricity, medium voltage	MJ	0.32		market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US
PV module EOL	kg	1		Table A17
transport, freight, lorry	kg*km	160		transport, freight, lorry, unspecified
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
average incineration residue	kg	0.2		treatment of average incineration residue, residual material landfill | average incineration residue | Cutoff, U - RoW
electricity, medium voltage	MJ	7.14	Avoid in avoided burden cases	electricity, from municipal waste incineration to generic market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RoW

Table A18. Inventory for Partial Recycling of PV Modules From Stolz et al. (2017), Modified to Reflect Supplementary Info Table S19 in Müller et al. (2021)

Input Flows	Unit	Amount	Avoid	Provider
aluminium, primary, ingot	kg	Avoided burden (AB) cases only: 5.62E-02		treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | aluminium, wrought alloy | Cutoff, U - RoW
Carbon dioxide, fossil	kg	AB cases only: 6.61E-03		treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RoW
copper, cathode	MJ	6.48E-02		diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO
heat, district or industrial, natural gas	kWh	1.11E-01		market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US
heat, district or industrial, other than natural gas	kg	1.00E+00		
lime, packed	t*km	5.00E-01		market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW
PV module EOL	kg	1		Table A17.
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
aluminium, primary, ingot	kg	5.62E-02	In avoided burden (AB) cases	aluminium production, primary, ingot | aluminium, primary, ingot | Cutoff, U - CA
Carbon dioxide, fossil	kg	-1.24E-01		Elementary flows/Emission to air/low population density
copper, cathode	kg	6.61E-03	In AB cases	copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, U - GLO
heat, district or industrial, natural gas	MJ	8.30E-01	In AB cases	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - RoW
heat, district or industrial, other than natural gas	MJ	5.38E-01	In AB cases	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW
lime, packed	kg	2.42E-01	In AB cases	lime production, milled, packed | lime, packed | Cutoff, U - RoW
silica sand	kg	3.50E-01	In AB cases	market for silica sand | silica sand | Cutoff, U - GLO
soda ash, light	kg	1.38E-01	In AB cases	market for soda ash, light | soda ash, light | Cutoff, U - GLO
waste plastic, mixture	kg	1.51E-01		treatment of waste plastic, mixture, sanitary landfill | waste plastic, mixture | Cutoff, U - RoW

waste plastic, mixture	kg	2.64E-02		treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW

Table A19. Inventory for Hypothetical High Recovery Recycling of PV Modules From Latunussa et al. (2016), Transportation Taken From Stolz et al. (2017)

Input Flows	Unit	Amount	Avoid	Provider
diesel, burned in building machine	MJ	4.00E-02		diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO
electricity, medium voltage	kWh	1.14E-01		market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US
lime	kg	3.60E-02		lime production, milled, loose | lime | Cutoff, U - RoW
nitric acid, without water, in 50% solution state	kg	7.08E-03		market for nitric acid, without water, in 50% solution state | nitric acid, without water, in 50% solution state | Cutoff, U - RoW
PV module EOL	kg	1.00E+00		Table A17
transport, freight, lorry, unspecified	t*km	5.00E-01		market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW
water, completely softened	kg	3.10E-01		market for water, completely softened | water, completely softened | Cutoff, U - US
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
aluminium scrap, post-consumer	kg	1.83E-01	In avoided burden (AB) cases	market for aluminium scrap, post-consumer | aluminium scrap, post-consumer | Cutoff, U - GLO
blast furnace sludge	kg	5.00E-02		treatment of blast furnace sludge, residual material landfill | blast furnace sludge | Cutoff, U - RoW
copper, cathode	kg	4.40E-03	In AB cases	copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, U - GLO
electricity, medium voltage	MJ	2.49E-01	In AB cases	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US
fly ash and scrubber sludge	kg	2.00E-03		treatment of fly ash and scrubber sludge, hazardous waste incineration | fly ash and scrubber sludge | Cutoff, U - RoW
glass cullet, sorted	kg	6.86E-01	In AB cases	market for glass cullet, sorted | glass cullet, sorted | Cutoff, U - RoW
heat, district or industrial, natural gas	MJ	5.03E-01	In AB cases	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - RoW
limestone residue	kg	3.06E-01		treatment of limestone residue, inert material landfill | limestone residue | Cutoff, U - RoW

Input Flows	Unit	Amount	Avoid	Provider
nitrogen oxides	kg	2.00E-04		Elementary flows/Emission to air/unspecified
silicon, metallurgical grade	kg	3.50E-02	In AB cases	market for silicon, metallurgical grade | silicon, metallurgical grade | Cutoff, U - GLO
silver	kg	5.00E-04	In AB cases	market for silver | silver | Cutoff, U - GLO
used cable	kg	1.00E-02		treatment of used cable | used cable | Cutoff, U - GLO
waste glass	kg	1.40E-02		treatment of waste glass, inert material landfill | waste glass | Cutoff, U - CH
waste plastic, mixture	kg	9.20E-02		treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW
waste polyvinylfluoride	kg	1.80E-02		treatment of waste polyvinylfluoride, municipal incineration | waste polyvinylfluoride | Cutoff, U - RoW
waste wire plastic	kg	6.70E-03		treatment of waste wire plastic, municipal incineration | waste wire plastic | Cutoff, U - RoW

Table A20. Inventory for Transformer EOL, Derived From Méndez et al. (2021) and Bergesen et al. (2014)

Input Flows	Unit	Amount	Avoid	Provider
copper, cathode	kg	4400		treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RoW
steel, unalloyed	kg	1800		steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW
2.7 MW_{ac} transformer EOL	Item(s)	1		Table A17
transport, freight, lorry, unspecified	t*km	1400		market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
copper, cathode	kg	4400	In avoided burden (AB) cases	
steel, low-alloyed	kg	1800	In AB cases	
waste plastic, mixture	kg	1050		market group for waste plastic, mixture | waste plastic, mixture | Cutoff, U - RER
waste reinforced concrete	kg	2400		treatment of waste reinforced concrete, recycling | waste reinforced concrete | Cutoff, U - RoW

Table A21. Inventory for Electrical Balance-of-System EOL, Derived From Méndez et al. (2021) and Bergesen et al. (2014)

Input Flows	Unit	Amount	Avoid	Provider
aluminium, wrought alloy	kg	0.31		treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | aluminium, wrought alloy | Cutoff, U - RoW
Electrical balance-of-system EOL (per module area)	m^2	1		Table A17
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
aluminium, primary, ingot	kg	0.31	In avoided burden cases	
waste polyvinylchloride	kg	0.11		market for waste polyvinylchloride | waste polyvinylchloride | Cutoff, U - RoW

Table A22. Inventory for Tracker EOL, Derived From Méndez et al. (2021) and Bergesen et al. (2014)

Input Flows	Unit	Amount	Avoid	Provider
aluminium, wrought alloy	kg	0.064		treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | aluminium, wrought alloy | Cutoff, U - RoW
steel, unalloyed	kg	9		steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW
1-axis tracker EOL (per module area)	m^2	1		Table A17
transport, freight, lorry, unspecified	t*km	0.5		market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
aluminium, primary, ingot	kg	0.064	in avoided burden (AB) cases	
steel, low-alloyed	kg	9	in AB cases	

Table A23. Inventory for Inverter EOL, Derived From Méndez et al. (2021) and Bergesen et al. (2014)

Input Flows	Unit	Amount	Avoid	Provider
2.7 MW_{ac} inverter EOL	Item(s)	1		Table A17.
aluminium, wrought alloy	kg	62		treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | aluminium, wrought alloy | Cutoff, U - RoW
copper, cathode	kg	330		treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RoW
steel, unalloyed	kg	1100		steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW
transport, freight, lorry, unspecified	t*km	400		market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW
Output Flows	**Unit**	**Amount**	**Avoid**	**Waste Treatment**
copper, cathode	kg	330	in avoided burden (AB) cases	
steel, low-alloyed	kg	1100	in AB cases	
waste plastic, mixture	kg	30		market group for waste plastic, mixture | waste plastic, mixture | Cutoff, U - RER
waste reinforced concrete	kg	2400		treatment of waste reinforced concrete, recycling | waste reinforced concrete | Cutoff, U - RoW
aluminium, primary, ingot	kg	62	in AB cases	

Appendix B. Impact Assessment

Table B1. Annual Energy Yield for 100-MWdc UPV System From NREL System Advisor Model

	Electricity to Grid (kWh)		
Year	**Fredonia, KS**	**Seattle, WA**	**Phoenix, AZ**
1	0	0	0
2	1.70E+08	1.25E+08	2.07E+08
3	1.69E+08	1.24E+08	2.06E+08
4	1.67E+08	1.23E+08	2.04E+08
5	1.66E+08	1.22E+08	2.03E+08
6	1.65E+08	1.21E+08	2.01E+08
7	1.64E+08	1.20E+08	2.00E+08
8	1.63E+08	1.20E+08	1.99E+08
9	1.62E+08	1.19E+08	1.97E+08
10	1.60E+08	1.18E+08	1.96E+08
11	1.59E+08	1.17E+08	1.94E+08
12	1.58E+08	1.16E+08	1.93E+08
13	1.57E+08	1.15E+08	1.92E+08
14	1.56E+08	1.15E+08	1.90E+08
15	1.55E+08	1.14E+08	1.89E+08
16	1.54E+08	1.13E+08	1.88E+08
17	1.53E+08	1.12E+08	1.86E+08
18	1.52E+08	1.11E+08	1.85E+08
19	1.51E+08	1.11E+08	1.84E+08
20	1.50E+08	1.10E+08	1.83E+08
21	1.49E+08	1.09E+08	1.81E+08
22	1.47E+08	1.08E+08	1.80E+08
23	1.46E+08	1.08E+08	1.79E+08
24	1.45E+08	1.07E+08	1.77E+08
25	1.44E+08	1.06E+08	1.76E+08
26	1.43E+08	1.05E+08	1.75E+08
27	1.42E+08	1.05E+08	1.74E+08
28	1.41E+08	1.04E+08	1.73E+08
29	1.40E+08	1.03E+08	1.71E+08
30	1.39E+08	1.02E+08	1.70E+08
31	1.38E+08	1.02E+08	1.69E+08
TOTAL	4,606,964,000	3,384,860,000	5,621,965,000

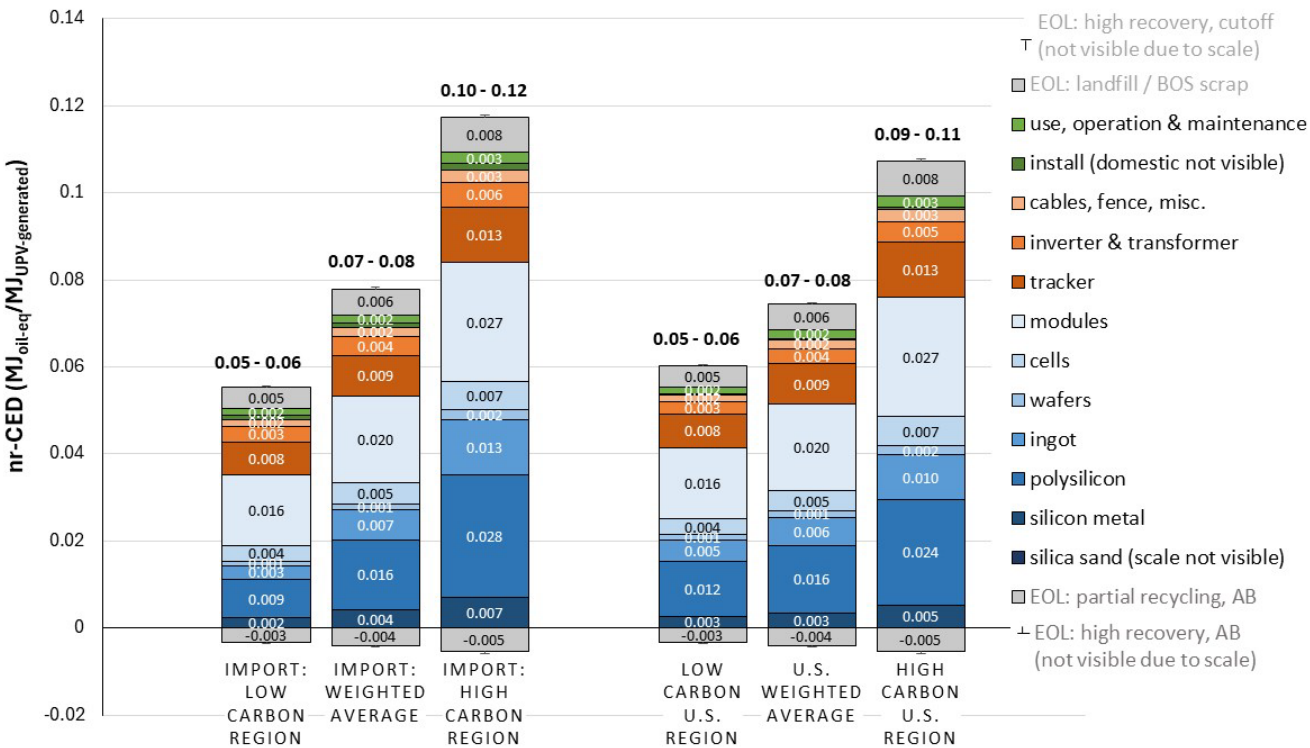

Figure B1. nr-CED per megajoule generated by UPV systems installed in the United States: 20.3% efficient monofacial PERC modules, single-axis tracker, 0.7% degradation rate, 30-year system life.

Low-carbon cases installed in Phoenix, AZ; **w**eighted average cases installed in Fredonia, KS; **h**igh-carbon cases installed in Seattle, WA; annual energy generation reported above in Table B1.

Table B2. CED (MJ_{oil-eq} per kW_{dc}) data from Figure 7

	CED (MJ_{oil-eq} per kW_{dc})		Import: low carbon region	Import: weighted average	Import: high carbon region	U.S. low carbon region	U.S. weighted average	U.S. high carbon region
PV module	Silica sand		10	14	18	3	3	3
	Silicon metal		470	670	840	560	580	650
	Polysilicon		1800	2700	3400	2500	2600	2900
	Ingots		660	1100	1500	1000	1100	1300
	Wafers		190	240	280	230	230	250
	PERC cell		740	800	800	760	770	820
	Module		3300	3300	3300	3300	3300	3300
BOS	Tracker		1700	1700	1700	1700	1700	1700
	Inverter/Transformer		780	780	780	780	780	780
	Cables, fence, misc.		380	380	380	380	380	380
Install	Installation		180	180	180	46	46	46
Use	Use, O&M		340	340	340	340	340	340
EOL	Landfill & BOS scrap	Cutoff	1000	1000	1000	1000	1000	1000
	Partial recycle & BOS scrap	AB	-1000	-1000	-1000	-1000	-1000	-1000
	High-recovery & BOS scrap	Cutoff	1100	1100	1100	1100	1100	1100
		AB	-1100	-1100	-1100	-1100	-1100	-1100

Table B3. CED ($MJ_{oil\text{-}eq}$ per $MJ_{UPV\text{-}generated}$) data from Figure 8

	CED ($MJ_{oil\text{-}eq}/MJ_{UPV\text{-}generated}$)		Import: low carbon region	Import: weighted average	Import: high carbon region	U.S. low carbon region	U.S. weighted average	U.S. high carbon region
PV module	Silica sand		0.000	0.000	0.000	0.000	0.000	0.000
	Silicon metal		0.002	0.004	0.007	0.003	0.003	0.005
	Polysilicon		0.009	0.016	0.028	0.012	0.016	0.024
	Ingots		0.003	0.007	0.012	0.005	0.007	0.011
	Wafers		0.001	0.001	0.002	0.001	0.001	0.002
	PERC cell		0.004	0.005	0.007	0.004	0.005	0.007
	Module		0.016	0.020	0.027	0.016	0.020	0.027
BOS	Tracker		0.008	0.010	0.014	0.008	0.010	0.014
	Inverter/Transformer		0.004	0.005	0.006	0.004	0.005	0.006
	Cables, fence, misc.		0.002	0.002	0.003	0.002	0.002	0.003
Install	Installation		0.001	0.001	0.001	0.000	0.000	0.000
Use	Use, O&M		0.002	0.002	0.003	0.002	0.002	0.003
EOL	Landfill & BOS scrap	Cutoff	0.005	0.006	0.008	0.005	0.006	0.008
	Partial recycle & BOS scrap	AB	-0.005	-0.006	-0.008	-0.005	-0.006	-0.008
	High-recovery & BOS scrap	Cutoff	0.005	0.006	0.008	0.005	0.006	0.008
		AB	-0.005	-0.006	-0.008	-0.005	-0.006	-0.008

Table B4. nr-CED ($MJ_{oil\text{-}eq}$) per $MJ_{UPV\text{-}generated}$ data from Figure B1

	CED ($MJ_{oil\text{-}eq}/MJ_{UPV\text{-}generated}$)		Import: low carbon region	Import: weighted average	Import: high carbon region	U.S. low carbon region	U.S. weighted average	U.S. high carbon region
PV module	Silica sand		0.000	0.000	0.000	0.000	0.000	0.000
	Silicon metal		0.002	0.004	0.007	0.003	0.003	0.005
	Polysilicon		0.009	0.016	0.028	0.012	0.016	0.024
	Ingots		0.003	0.007	0.013	0.005	0.006	0.010
	Wafers		0.001	0.001	0.002	0.001	0.001	0.002
	PERC cell		0.004	0.005	0.007	0.004	0.005	0.007
	Module		0.016	0.020	0.027	0.016	0.020	0.027
BOS	Tracker		0.008	0.009	0.013	0.008	0.009	0.013
	Inverter/Transformer		0.003	0.004	0.006	0.003	0.004	0.005
	Cables, fence, misc.		0.002	0.002	0.003	0.002	0.002	0.003
Install	Installation		0.001	0.001	0.001	0.000	0.000	0.000
Use	Use, O&M		0.002	0.002	0.003	0.002	0.002	0.003
EOL	Landfill & BOS scrap	Cutoff	0.005	0.006	0.008	0.005	0.006	0.008
	Partial recycle & BOS scrap	AB	-0.003	-0.004	-0.005	-0.003	-0.004	-0.005
	High-recovery & BOS scrap	Cutoff	0.005	0.006	0.008	0.005	0.006	0.008
		AB	-0.003	-0.004	-0.005	-0.003	-0.004	-0.005

Table B5. GHG emissions (kg CO_2e per kW_{dc}) data from Figure 9

	GHG emissions (kg CO_2e per kW_{dc})		Import: low carbon region	Import: weighted average	Import: high carbon region	U.S. low carbon region	U.S. weighted average	U.S. high carbon region
PV module	Silica sand		1	1	1	0	0	0
	Silicon metal		31	59	82	25	35	52
	Polysilicon		99	230	320	83	130	220
	Ingots		34	100	150	25	50	96
	Wafers		11	18	23	10	13	17
	PERC cell		65	68	70	53	59	71
	Module		210	220	220	210	210	220
BOS	Tracker		130	130	130	130	130	130
	Inverter & Transformer		38	38	38	38	38	38
	Cables, fence, misc.		30	30	30	30	30	30
Install	Installation		13	13	13	3	3	3
Use	Use, O&M		17	17	17	17	17	17
EOL	Landfill & BOS scrap	Cutoff	93	93	93	93	93	93
	Partial recycle & BOS scrap	AB	-62	-62	-62	-62	-62	-62
	High recovery & BOS scrap	Cutoff	110	110	110	110	110	110
		AB	-49	-49	-49	-49	-49	-49

Table B6. GHG emissions (kg CO_2e per kWh) data from Figure 10

	GHG emissions (g CO_2e per kWh)		Import: low carbon region	Import: weighted average	Import: high carbon region	U.S. low carbon region	U.S. weighted average	U.S. high carbon region
PV module	Silica sand		0.0	0.0	0.0	0.0	0.0	0.0
	Silicon metal		0.5	1.3	2.4	0.5	0.8	1.5
	Polysilicon		1.8	5.0	9.5	1.5	2.8	6.5
	Ingots		0.6	2.2	4.4	0.5	1.1	2.8
	Wafers		0.2	0.4	0.7	0.2	0.3	0.5
	PERC cell		1.2	1.5	2.1	0.9	1.3	2.1
	Module		3.7	4.8	6.5	3.7	4.6	6.5
BOS	Tracker		2.3	2.8	3.8	2.3	2.8	3.8
	Inverter & Transformer		0.7	0.8	1.1	0.7	0.8	1.1
	Cables, fence, misc.		0.5	0.7	0.9	0.5	0.7	0.9
Install	Installation		0.2	0.3	0.4	0.1	0.1	0.1
Use	Use, O&M		0.3	0.4	0.5	0.3	0.4	0.5
EOL	Landfill & BOS scrap	Cutoff	1.7	2.0	2.8	1.7	2.0	2.8
	Partial recycle & BOS scrap	AB	-1.1	-1.5	-2.0	-1.1	-1.5	-2.0
	High recovery & BOS scrap	Cutoff	2.0	2.4	3.3	2.0	2.4	3.3
		AB	-0.9	-1.1	-1.5	-0.9	-1.1	-1.5

Appendix C. EPBT and CPBT

Table C1. Global Warming Potential (GWP) Values Updated to the GridMix Explorer

Name	IPCC AR5, 2013, 100-yr, w/ climate carbon feedback (used by GridMix Explorer)	IPCC AR6, 2021, 100-yr, w/ climate carbon feedback
1,1,1-Trichloroethane	193	161
CFC-11	5350	6230
CFC-113	6586	6520
CFC-114	9615	9430
CFC-115	8516	9600
CFC-12	11547	12500
CFC-13	15451	16200
Carbon dioxide	1	1
Carbon tetrachloride	2019	2200
Carbon tetrafluoride	7350	7380
Chloroform	20	20.6
Chloromethane	15	5.54
Dibromomethane	1	1.51
HCFC-123	96	90.4
HCFC-124	635	597
HCFC-141b	938	860
HCFC-142b	2345	2300
HCFC-21	179	160
HCFC-22	2106	1960
HFC-125	3691	3740
HFC-134a	1549	1530
HFC-143a	5508	5810
HFC-23	13856	14600
HFC-236fa	8998	8690
HFC-32	817	771
Halon 1211	2070	1930
Halon 1301	7154	7200
Hexafluoroethane	12340	12400
Methane	36	27.9
Methyl bromide	3	2.43
Methylene chloride	11	11.2

Name	IPCC AR5, 2013, 100-yr, w/ climate carbon feedback (used by GridMix Explorer)	IPCC AR6, 2021, 100-yr, w/ climate carbon feedback
Nitrogen trifluoride	17885	17400
Nitrous oxide	298	273
Perfluorocyclobutane	10592	10200
Perfluoropropane	9878	9290
Sulfur hexafluoride	26087	24300

Table C2. Electric Grid Mix by State and Cambium Scenario

Note that the sum of the grid mix may not sum to 100% because some technologies modeled in Cambium are not modeled in NETL's Electricity Grid Mix Explorer tool (e.g., batteries).

	Kansas – Mid-Case							
	2024	**2026**	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**
BIOMASS	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
COAL	22.5%	9.2%	4.4%	3.8%	2.8%	1.9%	1.0%	0.7%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GEOTHERMAL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HYDRO	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MIXED	0	0	0	0	0	0	0	0
NUCLEAR	16.3%	10.8%	8.8%	8.7%	7.8%	7.4%	0.0%	0.0%
OFSL	0	0	0	0	0	0	0	0
OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OTHF	0	0	0	0	0	0	0	0
SOLAR	6.6%	13.8%	24.0%	28.2%	28.8%	28.6%	36.7%	39.3%
SOLARTHERMAL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WIND	52.9%	65.2%	62.1%	56.7%	56.1%	57.2%	52.9%	50.4%
SCPC	0	0	0	0	0	0	0	0
SCPC w/ CCS	0	0	0	0	0	0	0	0
SubPC	0	0	0	0	0	0	0	0
SubPC w/ CCS	0	0	0	0	0	0	0	0
NGCC	1.7%	1.0%	0.6%	0.4%	0.3%	0.2%	0.2%	0.2%
NGCC w/ CCS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

	Kansas – Mid-Case							
	2024	**2026**	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**
OxyPC w/ CCS	0	0	0	0	0	0	0	0
SOFC Coal Conventional Gasifier w/ CCS	0	0	0	0	0	0	0	0
SOFC NG w/ CCS	0	0	0	0	0	0	0	0
SubPC w/ CCS using NG	0	0	0	0	0	0	0	0
	Washington – Low Renewable Energy Cost							
	2024	**2026**	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**
BIOMASS	0.5%	0.5%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%
COAL	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%
GEOTHERMAL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HYDRO	77.4%	79.9%	78.7%	73.1%	71.4%	66.3%	63.1%	64.0%
MIXED	0	0	0	0	0	0	0	0
NUCLEAR	7.1%	7.0%	6.7%	6.4%	5.0%	0.0%	0.0%	0.0%
OFSL	0	0	0	0	0	0	0	0
OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OTHF	0	0	0	0	0	0	0	0
SOLAR	0.9%	1.4%	1.9%	3.1%	4.7%	4.6%	4.7%	4.6%
SOLARTHERMAL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WIND	7.3%	7.7%	10.6%	16.2%	17.2%	27.2%	30.0%	29.0%
SCPC	0	0	0	0	0	0	0	0
SCPC w/ CCS	0	0	0	0	0	0	0	0

	Kansas – Mid-Case							
	2024	**2026**	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**
SubPC	0	0	0	0	0	0	0	0
SubPC w/ CCS	0	0	0	0	0	0	0	0
NGCC	4.5%	3.5%	1.9%	1.1%	1.5%	1.7%	2.0%	1.9%
NGCC w/ CCS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OxyPC w/ CCS	0	0	0	0	0	0	0	0
SOFC Coal Conventional Gasifier w/ CCS	0	0	0	0	0	0	0	0
SOFC NG w/ CCS	0	0	0	0	0	0	0	0
SubPC w/ CCS using NG	0	0	0	0	0	0	0	0

	Arizona – High Renewable Energy Cost							
	2024	**2026**	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**
BIOMASS	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%
COAL	16.8%	16.6%	16.0%	12.3%	10.8%	8.8%	6.6%	4.8%
GAS	0.3%	0.2%	0.1%	0.1%	0.1%	0.3%	0.3%	0.2%
GEOTHERMAL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HYDRO	7.2%	8.8%	9.0%	10.0%	9.5%	8.6%	8.6%	10.0%
MIXED	0	0	0	0	0	0	0	0
NUCLEAR	30.8%	31.2%	32.2%	34.9%	33.1%	28.8%	23.7%	19.0%
OFSL	0	0	0	0	0	0	0	0
OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OTHF	0	0	0	0	0	0	0	0
SOLAR	12.2%	12.5%	13.7%	15.4%	21.6%	32.6%	44.4%	54.0%

	Kansas – Mid-Case							
	2024	**2026**	**2028**	**2030**	**2035**	**2040**	**2045**	**2050**
SOLARTHERMAL	0.6%	0.6%	0.6%	0.7%	0.7%	0.6%	0.0%	0.0%
WIND	1.7%	3.4%	3.9%	6.7%	6.3%	5.4%	4.3%	2.6%
SCPC	0	0	0	0	0	0	0	0
SCPC w/ CCS	0	0	0	0	0	0	0	0
SubPC	0	0	0	0	0	0	0	0
SubPC w/ CCS	0	0	0	0	0	0	0	0
NGCC	30.0%	26.2%	23.8%	19.1%	16.2%	12.2%	7.6%	4.9%
NGCC w/ CCS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OxyPC w/ CCS	0	0	0	0	0	0	0	0
SOFC Coal Conventional Gasifier w/ CCS	0	0	0	0	0	0	0	0
SOFC NG w/ CCS	0	0	0	0	0	0	0	0
SubPC w/ CCS using NG	0	0	0	0	0	0	0	0

Table C3. NREL Cambium Technology Definitions Assigned to NETL Grid Mix Explorer Technology Definitions

For most technology definitions, there exists a one-to-one relationship. In some cases, where there are multiple technologies for a given definition, the values are equally distributed. Some technologies modeled in Cambium are not present in Grid Mix Explorer e.g., batteries.

Grid Mix Explorer Technology Description	Cambium Technology and description
Biomass - Power plants where more than 90% of electricity generation is from combusting biomass fuels.	Biomass - Biopower and landfill gas
Coal - Power plants where more than 90% of electricity generation is from combusting coal.	Coal (scrubbed and unscrubbed, integrated gasification combined cycle, and biomass cofired)
Natural gas - Power plants where more than 90% of electricity generation is from combusting natural gas.	Natural gas combustion turbine

Grid Mix Explorer Technology Description	Cambium Technology and description
Geothermal - Power plants where more than 90% of electricity generation is geothermal energy.	Geothermal (hydrothermal, near-field enhanced geothermal, and deep enhanced geothermal systems)
Hydro - Power plants where more than 90% of electricity generation is from hydroelectric power.	Hydropower (existing and undiscovered, dispatchable and nondispatchable). Cambium treats Canadian imports as dispatchable hydropower.
Mixed - Power plants that use some mix of fuel - i.e., they don't reach the 90 percent threshold for being classified as a single fuel source. As a result, these plants represent different things based on the power plants that exist in the specified area of interest. That is, mixed power plants in CAISO will not have the same inventory as mixed plants in ERCOT.	
Nuclear - Power plants where more than 90% of electricity generation is from thermonuclear generation.	Nuclear (both conventional and small modular reactors)
Other fossil - Power plants where more than 90% of electricity generation is from combusting other fossil fuels (blast furnace gas, other gas, tire-derived fuel).	
Petroleum - Power plants where more than 90% of electricity generation is from combusting petroleum-based fuels (diesel fuel oil or residual fuel oil).	Oil-gas-steam
Other fuels - Power plants where more than 90% of electricity generation is from "other" fuels, including nonbiogenic MSW.	
Solar - Power plants where more than 90% of electricity generation is from solar photovoltaic cells.	Behind-the-meter PV, Utility-scale and distributed-utility-scale PV
Solar thermal - Power plants where more than 90% of electricity generation is from solar-thermal generation.	Concentrating solar power (with and without thermal energy storage)
Wind - Power plants where more than 90% of electricity generation is from wind turbines.	Offshore wind (fixed-bottom and floating) & Onshore wind
SCPC - Supercritical pulverized coal power plant.	Coal (scrubbed and unscrubbed, integrated gasification combined cycle, and biomass cofired)
SCPC w/ CCS - Supercritical pulverized coal power plant with carbon capture and storage in a saline aquifer.	Coal with carbon capture and storage
SubPC - Sub-critical pulverized coal power plant.	Coal (scrubbed and unscrubbed, integrated gasification combined cycle, and biomass cofired)

Grid Mix Explorer Technology Description	Cambium Technology and description
SubPC w/ CCS - Sub-critical pulverized coal power plant with carbon capture and storage in a saline aquifer.	Coal with carbon capture and storage
NGCC - Natural gas combined cycle power plant.	Natural gas combined cycle
NGCC w/ CCS - Natural gas combined cycle power plant with carbon capture and storage in a saline aquifer.	Natural gas combined cycle with carbon capture and storage
SubPC w/ CCS w/ NG Aux - Sub-critical pulverized coal power plant with carbon capture and storage in a saline aquifer. The steam and electricity load for the carbon capture system are provided by a natural gas simple cycle turbine.	

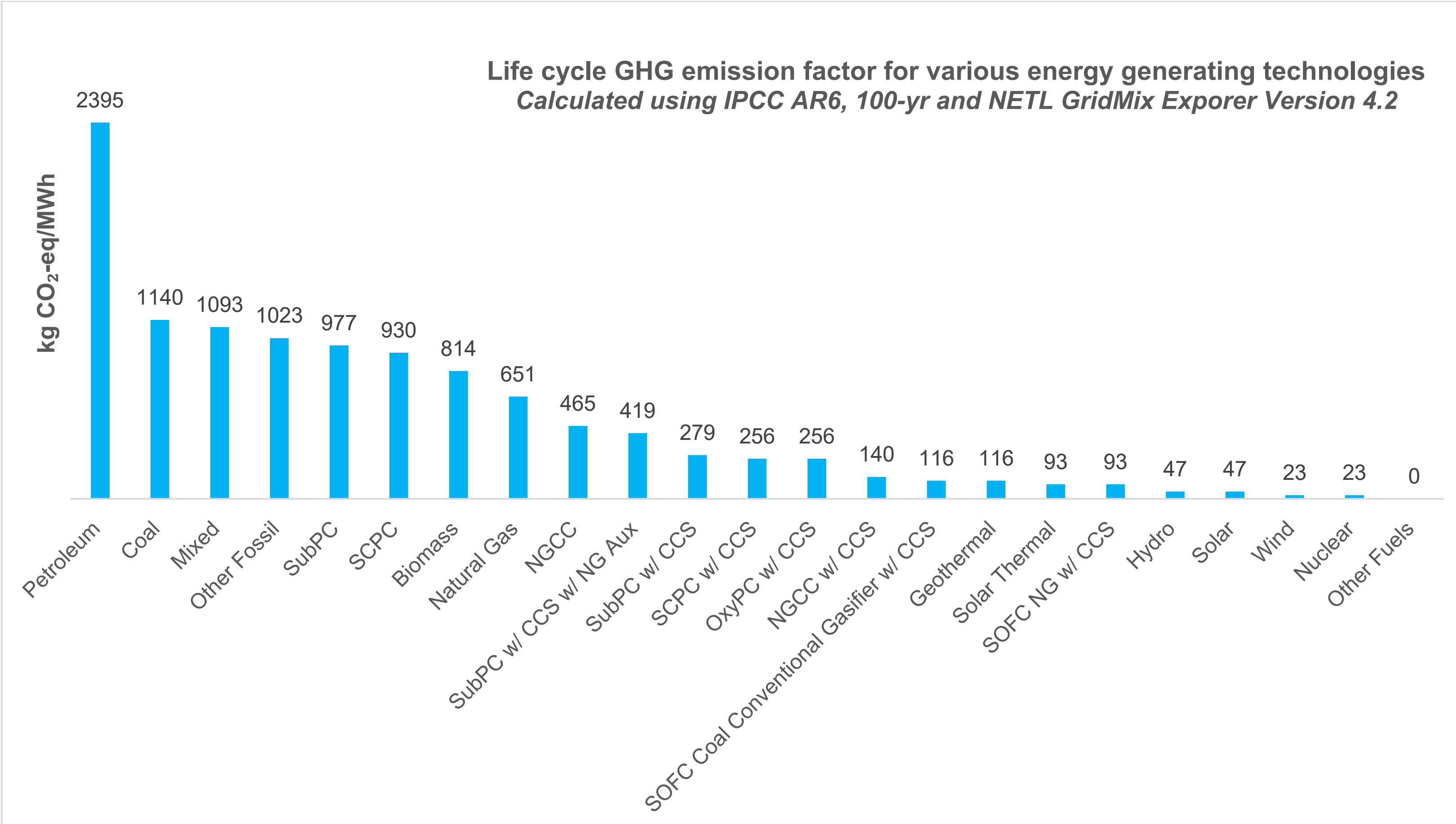

Figure C1. Life cycle GHG emission factor (kg CO_{2eq}/MWh) of various energy-generating technologies