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Public Life Cycle Inventory Data Gap Analysis for Silicon-based Residential Photovoltaic Systems

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Abstract

Given the increasing prevalence of using Environmental Product Declarations (EPDs) for product comparisons and selection, both domestically and globally, there is a need to ensure the results reported in EPDs are useful for such comparisons (i.e., transparent and standardized to ensure quality decision making). One challenge that was identified more than a decade ago was the lack of common data sources, which could undermine the comparability of EPDs and similar claims. Federal agencies have targeted this issue through the development of public secondary datasets and gap assessments of currently available public life cycle inventory (LCI) datasets.

This study follows the framework for the identification and quantification of public data gaps developed and applied to construction materials in NIST TN 2338 and expanded in and applied to a building system component (photovoltaic panels) in NIST TN 2350. This study addresses the final application of one semiconductor, a residential photovoltaic system. The LCA models developed in NIST TN 2350 are used as the photovoltaic panel components needed in this study to model the entire photovoltaic system. The scope of this study is to (1) refine the framework to identify public life cycle assessment (LCA) data gaps by evaluating multiple impact categories using two impact assessment methods, (2) identify and quantify the impact of each data gap of the components of an entire building system (i.e., rooftop residential photovoltaic system), and (3) provide qualitative rankings of data gaps both within each stage of the production supply chain and for the entire assembled system. The study concludes with a series of recommendations to strengthen and further develop public LCI datasets.

Keywords

Building systems; ISO 219130; FEDEFL inventory indicators, life cycle assessment; representative inventory; resources; photovoltaic; semiconductors; sustainability.

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Author Contributions

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Joshua Kneifel: Funding acquisition, Resources, Conceptualization, Supervision, Project administration, Writing- Reviewing and Editing.

1. Background/ Introduction

There has been growing interest from consumers, industry, local and state jurisdictions in the U.S., and nation states globally for improved reporting of the environmental and human health impacts associated product purchases [1–5]. A common approach to quantify these impacts is life cycle assessment (LCA), which provides a scientific methodology for calculating potential impacts of a product or service over its entire life cycle in accordance with the International Standards Organization (ISO) 14040 and ISO 14044 standards [6, 7]. While LCA is the quantification tool, product statements are the communication mechanism for providing decision-makers with information about a product's environmental impacts. ISO has established fundamental principles and requirements for various types of product statements in ISO 14020 [8], including Environmental Product Declarations (EPDs), whose requirement are further developed in ISO 14025 [9].

An EPD is a standardized third-party verified document that provides LCA-based information as well as additional information on the environmental aspects of products [9]. EPD programs are often built for specific product categories, groups of products capable of fulfilling equivalent functions that might require EPDs to be consistent with a distinct Product Category Rule (PCR) in addition to the aforementioned ISO standards. Efforts to harmonize the development and use of PCRs include ISO 14027 on development of PCRs and ISO 14029 on mutual recognition of EPDs and footprint communication programs [10, 11] as well as the PCR Open Standard from the American Center for Life Cycle Assessment (ACLCA) [12].

Using EPDs for documenting impacts of products has been common and growing since they were introduced into building rating systems [2]. Additionally, EPDs are being used as the basis for product selection by building construction companies and building owners as well as a range of U.S. jurisdictions and states [3, 4, 13]. Specifically, these programs require third-party verified EPDs compliant with ISO 14025 and ISO 21930 [14] standards for life-cycle stages A1-A3, known as “cradle-to-gate” because it includes impacts from raw material extraction through the product manufacturing, but excludes any impact after the product leaves the manufacturing site or “gate.” Along with domestic demand for products with EPDs, global demand is also growing as EPDs are increasingly being required in U.S. export markets [5].

Given the increasing prevalence of using EPDs for product comparisons and selection, both domestically and globally, there is a need to ensure the results reported in EPDs are useful for such comparisons. One challenge that was identified more than a decade ago was the lack of common data sources, which could undermine the comparability of EPDs and similar claims [15]. However, secondary data sources—i.e., not specific to a manufacturer and a product—are still lacking, and those available are often commercial products and not necessarily representative of U.S. industrial practices.

Federal agencies have formalized collaboration to improve LCA secondary data through an interagency initiative, the Federal LCA Commons (FLCAC) [16]. Activities of the FLCAC include providing support to enhance standardization, measurement, reporting, and verification of LCA modeling. These activities will assist industry in improving the transparency, trustworthiness, and comparability of results reported in EPDs, and improving their competitiveness in domestic and global marketplace. Some agencies have already undertaken activities to identify secondary LCA data needs for EPD development with specific focus on construction materials. As part of those activities, NIST developed a framework for the identification and quantification of data gaps, and applied it across several product categories of construction materials [17] and a building system component [18].

This study is designed to complement Ref. [17] and Ref. [18] by refining the range of potential impacts included in the framework and apply to a building system. A building system that relies on semiconductor materials, photovoltaic panels, was selected in Ref. [18] to align with multiple NIST research programs (e.g., Measurement Science for Building Systems Program and Circular Economy). Ref. [18] can inform supply chain analysis for similar semiconductors and semiconductor-based products, including those in the energy sector, to accelerate the accuracy and trust in company statements claims of these products. This study addresses the final application of one semiconductor, the production of electricity through a residential photovoltaic system.

The scope of this study is to:

(1) Refine the existing framework to assess gaps based on mass input and nine potential impacts, including mineral resources depletion and water use.
(2) Identify and quantify the impact of data gaps across all the components that constitute a photovoltaic system.
(3) Provide qualitative rankings of data gaps within and across production supply chain of photovoltaic systems.

Additionally, possible sources to fill some of the data gaps identified are offered.

2. Methodology

The data gap analysis method applied here is explained in detail in NIST TN 2338 [17] and NIST TN 2350 [18]. What follows is the description of how this methodology was implemented for a residential photovoltaic system, together with any differences relative to the original methodology.

2.1. Inventory identification, representative inventory dataset selection, and round robin modeling

Part of Task 12 of the Photovoltaic Power Systems (PVPS) Program of the International Energy Agency (IEA) is directed towards the development of Life cycle inventory (LCI) and Life cycle assessment (LCA) related data on an array of technologies related to PVs. Using the latest LCI for PV systems published on Ref. [19], Krebs et al. built inventories for a 10 kW_P residential photovoltaic system that is used here to develop representative inventories for said systems [20] as shown in Figure 1. The commercial database ecoinvent (EI) includes similar inventories to those in PVPS for 3 kW_P systems based on dated reports that were also adapted and updated by PVPS [21, 22]. Thus, commercial inventories are not used here as a source for data gap analysis as was done in TN 2338 [17]. Nevertheless, they are included to (1) highlight differences between the two sources and (2) help identify potential modeling errors when creating the representative models, as in NIST TN 2350 [18]—Table 1.

Table 1 Round-robin model numbering.

Model	Inventory	Database	Information provided
#4	Commercial	Commercial	Reference and limited model verification
#5	Representative	Public	Gap identification when production/treatment process is absent from USLCI
#6	Representative	Commercial	Gap quantification

Note: Model #1 through Model #3, present in NIST TN 2338 [1], are excluded because the Federal LCA Commons (FLCAC) does not currently have model for the systems evaluated here. Model #7 is excluded because there is no representative database or product category rule (PCR).

The inventories presented in Ref. [20] are for a residential system in Switzerland. This affects how much electricity the system produces, but not the relative importance of the data gaps present in the system, which is the focus of this assessment.

V1.2025-03.0 [23] of the USLCI database was used throughout this analysis, as opposed to V1.2024-12.0 [28] used in NIST TN 2350 [18] and V1.2024-06.0 [29] in Ref. [23]. The most noticeable difference is that the newest update to USLCI includes models for wastewater treatment, which had previously been identified as data gaps.

OpenLCA [23] was used to build all models, and two terms common to this program are used throughout the report: exchanges and providers. Exchanges are inputs or outputs in a process, which in addition to the flow itself and the quantity of the flow that enters/leaves the process, it also includes its provider. If the exchange is an input, a provider is its source—e.g. a process producing a product. If the exchange is an output, the provider is the sink—e.g., a process treating a waste.

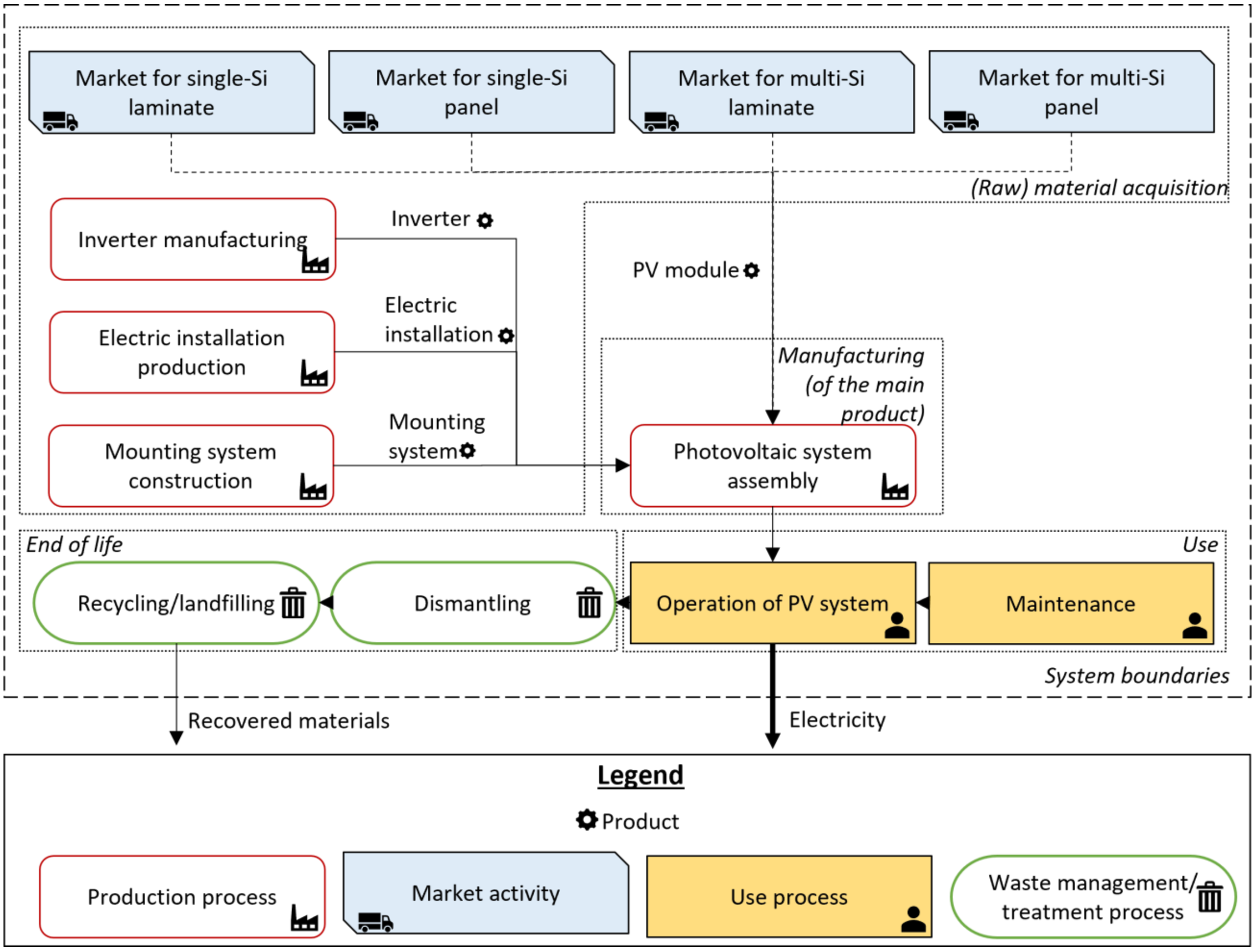


Figure 1 System boundaries of PV electricity production, adapted from Ref. [19]

2.2. Impact assessment categories and inventory indicators

As in NIST TN 2338 [17] and NIST TN 2350 [18], "a data gap is defined as a process (unit or system) that either produces or treats an environmentally relevant flow present in the inventory under assessment through a production/treatment that is considered equivalent to that described in the inventory—i.e., fit for purpose." Like in Ref. [18], mass input and the five impact categories required to be reported in an environmental product declaration (EPD) according to ISO 21930 [14]: global warming (GWP), acidification (AP), eutrophication (EP), ozone depletion (ODP), and photochemical oxidant creation (POCP) potential were assessed in this report. To streamline the procedure, the additional categories required or recommended by ISO 29130 were taken from the Federal LCA Commons Environmental Flows List (FEDEFL) Inventory Methods [24]: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), and water resources (WATER). This is in opposition to Ref. [18], where these indicators were taken from two Life Cycle Impact Assessment (LCIA) methodologies—ReCiPe [25, 26] and Cumulative Energy Demand (CED) [27, 28]—and additional calculations needed to be performed. Section 4.1. presents a comparison between the results of these four categories, and the equivalent ones selected in Ref. [18] for two models evaluated in this report.

Like in Ref. [18], based on the criteria found in Section 7.1.9 of ISO 21930 [14], any data gap contributing more than 1 % to an impact category is referred to as priority, key, or critical data gap interchangeably. This classification is impact category specific, as a data gap can be a priority based on GWP, and not a priority based on EP. Impact categories are not ranked here and are not necessarily seen as equally important. Nevertheless, gaps labeled as a priority for multiple categories are likely to be considered more (qualitatively) important than those labeled a priority in fewer categories. For the sake of brevity, throughout the text “priority data gap” is short for “priority data gap in at least one impact category”.

It is worth stressing that LCA addresses potential impacts and does not predict absolute or precise impacts due to [6]:

- The relative expression of impacts to a reference unit.
- The integration of data over space and time.
- The inherent uncertainty in modeling impacts.
- The fact that some possible impacts are clearly future ones.

Additionally, these models are often based on industrial averages instead of data from a single facility or location. For example, the amount of transport required for the installation of two PV systems that are otherwise identical will depend on the distance between suppliers and the construction site. Because the purpose of this report is to conduct a data gap analysis on PV system and develop public reference models, this level of precision is not required. Thus, the conclusions drawn as part of this study apply to generic, average products, not to specific installations.

3. Analysis

This section describes the implementation of the methodology defined in Section 2 to complete LCA modeling and analysis. It also includes a summary of the findings for each product within the PV system supply chain evaluated in this study and based on Krebs et al.'s residential PV system [20]: 10 kW_P panels with a centralized string inverter and electric installation, mounted on a slanted roof—Figure 1 and Table 2. To be consistent with Ref. [18], single silicon (Single Si) panels were used, and not multi Silicon (multi-Si) as in Ref. [20].

Table 2 Reference unit and expected lifetime of the components/stages under assessment

	Reference unit	Expected lifetime	Section
2.5 kW inverter (String inverter)	1 unit	15 years [20]	3.1
500 W inverter (Microinverter)	1 unit	30 years (assumed)	3.2
String optimizer	1 unit	15 years (assumed)	3.3
3 kW_p electric subsystem (excludes inverter)	1 unit	30 years [25]	3.4
Slanted roof mounting subsystem	1 m^2	30 years [25]	3.5
10 kW_P single-Si panel slanted roof system	1 unit	30 years [25]	3.6
Recycling of silicon panel	1 kg	-	3.7

In addition to the components of Krebs et al. system, additional components of residential PV systems were analyzed in this report. Microinverters (Section 3.2) are used as an alternative to inverters, and optimizers (Section 3.3) are used in combination with string inverters [29]. They are evaluated here to identify and quantify data gaps related to inverter technology selection. A recycling process for silicon panels has also been assessed in Section 3.7. Models for these components were also developed as part of this analysis and are made publicly available—see Appendix B.

Since the model for multi-silicon panel was developed as part of Ref. [18], no data gap analysis was performed for it in this report. Maintenance and dismantling activities, present in Figure 1, were not modeled independently. Maintenance was modeled as part of the PV panel system and of electricity production, although this last process is not modeled here. In the panel system, 3 % more panel area than what is required based on panel efficiency is included, 1 % representing rejects and 2 % replaced modules. Ref. [20] included water for cleaning as part of the use-phase of the panel. Dismantling was modeled as part of recycling as the transport between the home and the recycling facility.

The ensuing subsections all follow the same structure. First, in 3.X, a succinct technical description of the product and/or its production process. Then, in 3.X.1, the representative (Rep.) and commercial inventory (EI, from ecoinvent) are compared and its differences highlighted. When applicable, the modeling choices selected to build the representative model with EI processes—Model #6—are explained if they differ from those used by the commercial database to build theirs—Model #4. Data gaps, which are identified as a result of building the representative models with public datasets—Model #5—are listed and briefly compared to those from similar production processes. In 3.X.2, a table is provided with the relative contribution of all data gaps identified to the impact categories and indicators introduced in Section 2.2. The results of that table are initially discussed based on mass input. Then, a figure with the GWP of all three models is presented and discussed, first in general terms and then focusing on the contribution data gaps make to this impact category. This category was chosen to be consistent with previous NIST Technical Note 2338 [17] and NIST Technical Note 2350 [18]. For brevity, figures for other impact categories and indicators have not been included in the appendices of this report as was done in Ref. [18]. However, other impact category results are available in the "Figures" worksheet of their corresponding workbook—see Appendix B for details. The main text addresses those situations when the results from these other categories differ significantly from those of GWP. Finally, in 3.X.3 results are summarized in a table that include only priority data gaps—i.e., those contributing more than 1 % to at least one impact category. Data gaps for categories other than mass and GWP are discussed as well as any potential suggestion on prioritizing the filling of those data gaps.

3.1. 2.5 kW inverter

Inverters convert the direct current generated by a photovoltaic (PV) module into alternating current that can be fed into the grid or used within a home system. In addition, the inverters modeled here transform the electricity to low voltage.

3.1.1. Modeling and data gap identification

Krebs et al. (2020) used an inverter with an output power of 2.5 kW [20]. Inventories for 2.5 kW, 5 kW, 10 kW, and 20 kW were available in , Ref.[19], each of which will be made available as part of this project—see Appendix B. However, because the mass of all four inverters is extrapolated as a function of their power, the relative contributions of their components to any impact category are identical. Therefore, each inverter does not need to be assessed separately as part of this data gap analysis.

Frischknecht et al.'s inventories used here as the representative inventory are based on a Ref. [30], whose explicit purpose was to update the existing data in the commercial database. Therefore, the representative inventory (Rep.) is identical to the EI inventory. The one difference, mentioned often in Ref. [18], is that the original reports explicated the amount of train and truck transport—and thus, so does the Rep. LCI—while EI models transport only as part of market processes. To minimize double-counting transport, production processes, and not market activities were used whenever possible while building Inverter #6. The exception for which market activities where selected are:

- Cast alloy aluminum
- Copper
- Wastewater treatment

All selected production processes were for the Global (GLO) or Rest-of-World (ROW) geographies, except for corrugated board box, for which U.S. could be selected. For both Inverter #4 and Inverter #6 "market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US" was selected as the provider for production.

The 35 data gaps identified are included in Table 3. Note that bar extrusion is a data gap the same way clinker was for cement production in TN 2338 [17]. In USLCI, there is no dedicated dataset for the extrusion of aluminum bars. However, the dataset "Aluminum, extrusion, at plant - RNA" include this activity in addition to the raw material. Therefore, although the impacts of extrusion alone cannot be quantified for Inverter #5, they are included in the model.

Table 3 Data gaps identified for 2.5 kW inverter

Logic integrated circuit (IC)	Tin	>2 cm capacitor
Printed wiring board (PWB)	Copper	Film capacitor
Surface mounted (SMD) transistor	Bar extrusion	Waste paperboard
Through-hole mounting (TH) transistor	Memory IC	Factory
Miniature radio frequency chip inductor	Wire drawing	Polycarbonate
Glass diode	>2 cm capacitor	Sheet rolling
Wire clamp	Ferrite	SMD resistor
Plugs (for network cable)	TH resistor	Cable without plugs
Ring core choke inductor	SMD capacitor	Waste PWB
Municipal solid waste (MSW)	Metal working	Waste polyethylene (PE)
(Low voltage) Transformer	Hazardous waste	Tap water
Light emitting diode (LED)	Cable with plugs	

3.1.2. Modeling Results

In the following subsections, the magnitude of the data gaps identified in Section 3.1.1 are discussed based on (1) share of material inputs, (2) GWP, and (3) other impact categories. Table 4 reports the results across these three assessments.

Table 4 Data gaps' impacts for 2.5 kW inverter production (% of total impact)

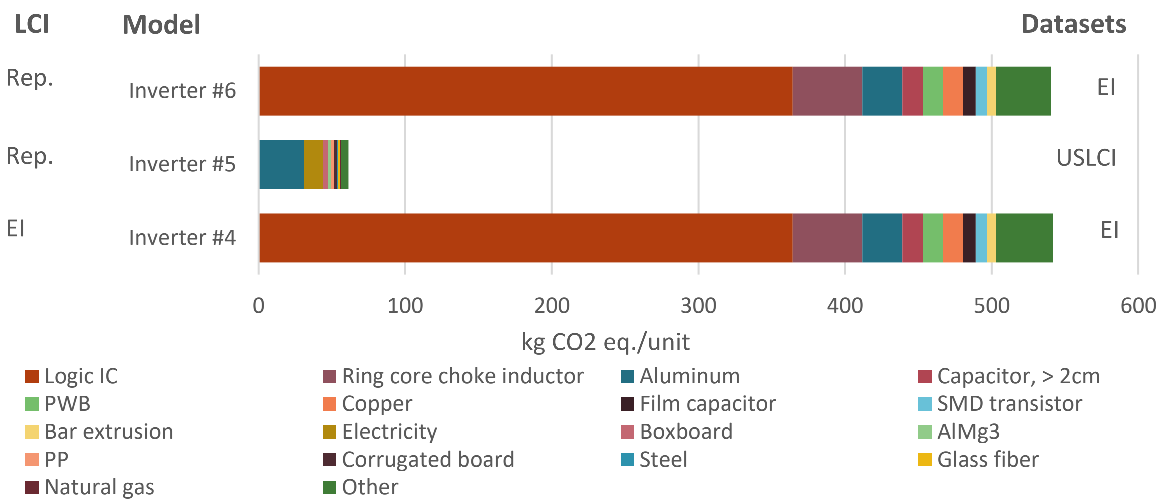
	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Logic IC	0.7	67.4	52.3	75.0	91.7	68.3	68.7	61.2	46.5	67.7
Ring core choke inductor	3.0	8.8	6.3	4.2	2.0	7.5	9.3	7.7	7.1	8.9
Capacitor, > 2cm	0.8	2.6	1.7	1.1	1.3	2.1	2.6	2.4	1.7	2.6
PWB	NA	2.6	2.6	1.4	0.7	2.1	2.5	2.4	7.7	2.4
Copper	5.7	2.6	22.8	10.9	0.5	7.2	2.3	5.4	9.4	5.4
Film capacitor	0.5	1.6	1.7	1.0	0.7	1.4	1.6	1.5	1.5	1.7
SMD transistor	0.1	1.4	2.0	1.1	0.3	1.4	1.5	1.6	1.4	1.8
Bar extrusion	NA	1.1	0.7	0.5	0.2	0.8	1.1	1.6	0.7	1.0
TH transistor	<0.1	0.7	0.9	0.5	0.1	0.7	0.7	0.7	0.7	0.8
Waste paper	NA	0.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Memory IC	<0.1	0.4	0.3	0.2	0.8	0.3	0.4	0.4	0.3	0.4
Factory	NA	0.3	0.3	0.1	<0.1	0.3	0.2	0.7	12.0	0.1
Wire drawing	NA	0.3	1.0	0.5	<0.1	0.4	0.3	0.4	0.5	0.4
Polycarbonate	0.6	0.3	0.1	<0.1	0.2	0.2	0.3	0.1	0.4	0.1
TH glass diode	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.1
Capacitor, <2cm	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sheet rolling	NA	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Wire clamp	<0.1	<0.1	0.2	0.1	<0.1	<0.1	<0.1	0.1	0.3	<0.1
MSW	NA	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
SMD resistor	*<0.1*	*<0.1*	*0.4*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Plug	*NA*	*<0.1*	*0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.3*	*<0.1*
Transformer	*0.1*	*<0.1*	*0.2*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.1*	*<0.1*
Miniature RF chip inductor	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Tin	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
SMD capacitor	*<0.1*	*<0.1*	*0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Cable without plugs	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Ferrite	*0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Metal working	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Waste PWB	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
TH resistor	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Hazardous waste	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Waste PE	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
LED	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Cable with plugs	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Tap water	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
TOTAL	11.7	91.1	94.0	97.1	98.5	93.5	92.1	86.7	91.0	93.8

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

Table 4 shows that despite the large number of data gaps identified, only three contribute more than 1 % to material inputs. Those are ring core choke inductor, copper, and tap water. Together they represent more than 70 % of the total inputs. However, if tap water is discarded, this amount is reduced to less than 12 %. These results might not be fully representative because three items that are material inputs—printed wiring board (PWB), plugs, and cable without plugs—are not reported in mass units—m^2, number of items, and m respectively. Because their mass is not known, it cannot be determined whether they are priority data gaps based on mass.

Figure 2 shows the impact of the two models built using EI datasets—Inverter #4 and Inverter #6—differ by less than 0.3 %. This is a direct consequence of both their inventories being based on the same data source as discussed in Section 3.1.1. It also indicates that the choices made while modeling Inverter #6 do not differ significantly from those made by the commercial database. The difference between the two models based on Rep., Inverter #5 and Inverter #6, are significant. The impact of the model using USLCI datasets—Inverter #5—is 10 % of the one built using EI datasets—Inverter #6. This difference is almost entirely driven by the data gaps, which are responsible for more than 90 % of the impact generated during the production of Inverter #6, as shown in Table 4. The logic type integrated circuit (IC) alone is responsible for more than two thirds of the impact—67 %. Seven other data gaps are a priority based on GWP: ring core choice inductor, >2 cm and film capacitors, PWB, copper, surface mounded (SMD) transistor, and bar extrusion. The remaining 27 gaps cause less than 3.5 % of the GWP of Inverter #6.



Only processes contributing >1 % to the GWP of at least one model are shown.

Figure 2 Global warming potential of 1 unit of 2.5 kW inverter

Other categories present very similar results to those of GWP—see Appendix B. Impacts of Inverter #4 and Inverter #6 are practically identical and are roughly an order of magnitude higher than those of Inverter #5. The one exception is Non-renewable energy, where the impact of Inverter #5 is almost 700 times greater than that of the other two models—see sheets "Figures" and "Fig NON-RE" on the "Inverter" workbook. The reason is the same as for the PV panel in Ref. [18]: EI's "market for aluminum, cast alloy | Cutoff, U - GLO" requires approximately 3.8E-6 kg uranium (Resource/ground/subterranean)/kg Al. Contrarily, USLCI's dataset "Aluminum, extrusion, at plant - RNA" requires approximately 2.5 kg U/kg Al (Resource/ground/subterranean)/kg Al.

As shown in Table 5, in addition to the priority data gaps based on mass input and GWP, the factory is a priority data gap based on MIN—contributing 12 % to this category. In addition, wire drawing is a priority based on AP, as it contributes 1 % to this category. Logic IC is not a priority based on mass, but it is based on all other indicators. Its contribution ranges between 46 %—MIN—to 92 %—ODP. Although not as impactful, ring core choke inductor, >2 cm capacitor, PWB, and copper are also priority data gaps for all indicators except mass input. Film capacitor, SMD transistor, and bar extrusion are data gaps for fewer, yet multiple indicators. Therefore, despite inverter's LCI having 35 data gaps, only 10 are a priority for at least one category. Because most of these are a priority for multiple indicators, filling them will offer more complete results, almost regardless of the indicators of interest.

Table 5 Priority data gaps' impacts for 2.5 kW inverter production (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Logic IC	*0.7*	67.4	52.3	75.0	91.7	68.3	68.7	61.2	46.5	67.7
Ring core choke inductor	3.0	8.8	6.3	4.2	2.0	7.5	9.3	7.7	7.1	8.9
Capacitor, > 2cm	*0.8*	2.6	1.7	1.1	1.3	2.1	2.6	2.4	1.7	2.6
PWB	*NA*	2.6	2.6	1.4	*0.7*	2.1	2.5	2.4	7.7	2.4
Copper	5.7	2.6	22.8	10.9	*0.5*	7.2	2.3	5.4	9.4	5.4
Film capacitor	*0.5*	1.6	1.7	*1.0*	*0.7*	1.4	1.6	1.5	1.5	1.7

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
SMD transistor	*0.1*	1.4	2.0	1.1	*0.3*	1.4	1.5	1.6	1.4	1.8
Bar extrusion	*NA*	1.1	*0.7*	*0.5*	*0.2*	*0.8*	1.1	1.6	*0.7*	1.0
Factory	*NA*	*0.3*	*0.3*	*0.1*	*<0.1*	*0.3*	*0.2*	*0.7*	12.0	*0.1*
Wire drawing	*NA*	*0.3*	1.0	*0.5*	*<0.1*	*0.4*	*0.3*	*0.4*	*0.5*	*0.4*

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

3.2. 500 W inverter

Microinverters are inverters installed for each individual panel, as opposed to the centralized inverters assessed in Section 3.1 In [PV][2], microinverters were modeled using a 500 W inverter from the commercial database [29]. The inventory for these inverters were originally included in Ref. [21], which is used here to develop the reference inventory because Ref. [30] did not update the inventory of these inverters.

3.2.1. Modeling and data gap identification

Because the commercial and representative inventories are from the same source, they are quantitatively identical. The one exception is the emission of waste heat, which was not included in EI. Somewhere between a quantitative and a qualitative difference is the fact that although both inventories have the same amount of PWB, EI splits PWB evenly between surfaces containing Pb and Pb-free surfaces. In the Microinverter #6 model, only the latter was used, consistent with Inverter #6 modeled in Section 3.1. A qualitative difference is that while Ref. [21] reported waste paper as an output—i.e. "disposal, packaging cardboard, 19.6% water, to municipal incineration"—the commercial database modeled waste paper as a negative input—"waste paperboard, unsorted, Recycled Content cut-off | waste paperboard, unsorted | Cutoff, U - GLO". For Rep., the original reference was followed.

As in Ref. [18] and Section 3.1, transport was explicitly included in the Rep. inventory, and thus included in Microinverter #6 with production processes selected whenever possible. The exceptions for which market activities were selected are:

- Cast alloy aluminum
- Copper
- HDPE
- Polystyrene foam slab

All production processes selected were for the GLO or ROW geographies except for corrugated board box, for which U.S. could be selected. In addition, "market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US" was selected as provider for both Microinverter #4 and Microinverter #6.

Table 6 shows the 24 data gaps identified for the microinverter, 18 of which appeared in the string inverter assessed in Section 3.1.. Of the six new data gaps, three are similar to other gaps present in the string inverter:

- Tantalum capacitor—there are other capacitors present in the string inverter
- High voltage transformer—the string inverter has a low voltage transformer
- Plastic waste—the string inverter has MSW

Table 6 Data gaps identified for 2.5 kW inverter

Logic IC	Bar extrusion	Waste PWB
PWB (Pb free)	Wire drawing	Waste PE
TH transistor	TH resistor	*(High voltage) Transformer*
Factory	>2 cm capacitor	*Tantalum Capacitor*
Glass diode	Film capacitor	*Waste PS*
Wire clamp	Waste paperboard	*Waste plastic*
Ring core choke inductor	Polycarbonate	*PE fleece*
Copper	Sheet rolling	*Styrene Acrylonitrile copolymer*

Note: Italicized gaps did not appear in the string inverter assessed in Section 3.1

3.2.2. Modeling Results

In the following subsections, the magnitude of the data gap identified in Section 3.2.1 are discussed based on (1) share of material inputs, (2) GWP, and (3) other impact categories. Table 7 reports the results across these three assessments.

Table 7 Data gaps' impacts for 500 W inverter production (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Logic IC	0.2	19.5	18.2	36.0	49.4	23.8	21.6	14.1	9.7	22.5
PWB wo Pb	NA	16.1	19.4	14.8	7.8	16.1	16.9	12.1	35.2	17.6
Film capacitor	2.4	7.2	9.5	7.6	5.7	8.0	8.2	5.5	4.9	8.8
Ring core choke inductor	2.5	6.9	6.0	5.5	2.9	7.1	8.0	4.8	4.0	8.1
Capacitor, > 2cm	1.8	5.8	4.5	3.9	5.2	5.6	6.4	4.3	2.7	6.6
Glass diode	0.3	5.4	4.9	3.9	2.2	5.3	6.0	4.1	2.3	6.1
Transformer	10.4	3.6	7.5	5.3	3.2	4.6	4.1	2.9	5.0	4.7
Waste paper	NA	3.6	0.1	0.1	<0.1	0.2	<0.1	<0.1	0.4	<0.1
TH transistor	0.3	2.9	5.0	3.8	1.0	3.6	3.3	2.6	2.2	4.1
Bar extrusion	NA	1.7	1.2	1.2	0.5	1.4	1.8	1.9	0.8	1.8
Ta capacitor	0.2	1.5	2.1	1.5	11.5	3.0	1.4	1.7	3.2	3.6
Wire clamp	1.7	1.4	6.0	4.1	0.7	2.5	1.5	1.8	4.5	2.1
Waste plastic	NA	1.4	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	0.1	<0.1
Polycarbonate	2.3	0.9	0.6	0.5	1.1	0.8	1.1	0.4	0.9	0.5
Waste PS	NA	0.6	<0.1	0.8	<0.1	<0.1	<0.1	<0.1	0.1	<0.1
Factory	NA	0.3	0.3	0.2	0.1	0.4	0.2	0.5	8.7	0.1
Fleece PE	1.0	0.2	0.1	0.1	0.3	0.2	0.3	<0.1	0.2	0.1
Waste PE	NA	0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
TH resistor	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sheet rolling	NA	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Waste PWB	NA	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

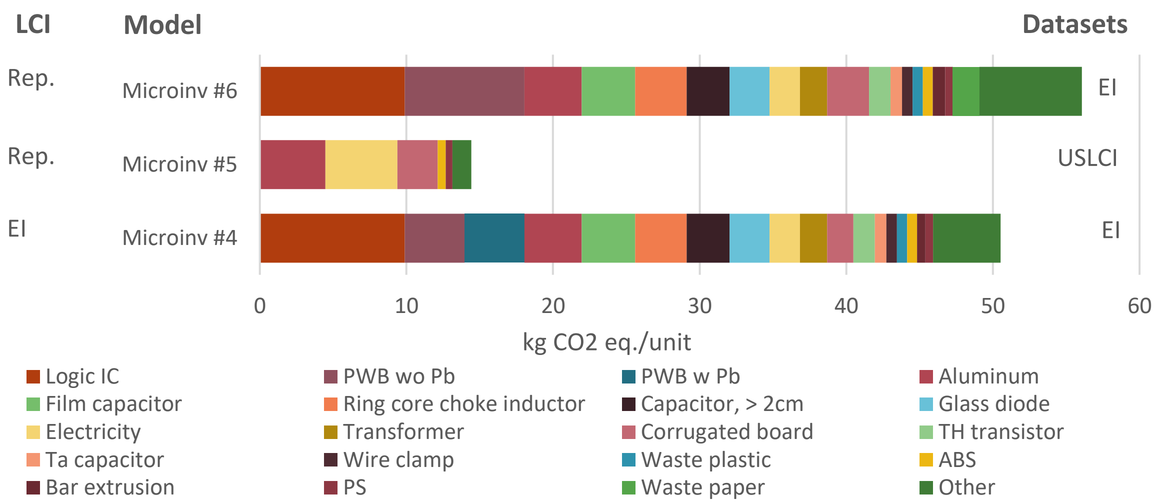
Copper	*<0.1*	*<0.1*	*0.3*	*0.2*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Styrene-acrylonitrile	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Wire drawing	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
TOTAL	23.2	79.3	86.1	89.9	91.5	83.2	81.1	56.9	85.2	87.0

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

Data gaps account for 22.4 % of the material input mass, as shown in Table 7, 10.4 % due to the transformer. Most of the remaining gap—11.7 % of the total mass input—is due to six other priority gaps: film and >2 cm capacitor, ring core choke inductor, wire clamp, polycarbonate, and fleece polyethylene (PE).

Figure 3 shows that the differences between the models built with EI processes are more significant for microinverters than string inverters (Figure 2). Microinv. #6 ‘s GWP impact is about 7 % greater than Microinv. #4’s due to the modeling choices discussed in Section 3.2.1. Two reasons are the higher impact of the U.S. Corrugated board used in Microinv. #6 when compared to the European corrugated board used in Microinv. #4 (60 % higher) and bar extrusion (50 % higher). The “others” group is also 52 % higher for Microinv. #6 that, unlike in Microinv #4, includes transport. Finally, “waste paper” appears in Figure 4 for Microinv. #6 but not in Microinv. #4 because the negative input chosen by the commercial database in Microinv. #4 is burden free. Because the treatment of waste paper is responsible for more than 3 % of Microinv. #6’s GWP impact, it may be necessary to clarify the boundaries between the waste generated by the production of inverters and paper recycling. In Microinv. #6, the burden of treatment is applied to the microinverter producer while in Microinv. #4 it is the paper recycler that is responsible for the treatment.

Although the differences between Microinv. #6 and Microinv. #5 are smaller than for the string inverters, the GWP impact of the microinverter is 3.8 times higher than the string inverter largely due to the data gaps. As seen in Table 7, gaps are responsible for 79 % of Microinv. #6’s GWP impact. As was the case for string inverter, the logic IC is the largest data gap, even if its relative importance is noticeably smaller than in the previous case—19.5 %. Five other priority data gaps are shared with the larger inverters: ring core choice inductor, >2 cm and film capacitors, PWB, and bar extrusion. Seven more additional priority data gaps are identified: glass diode, transformer, wastepaper and plastic, TH transistor, tellurium capacitor, and wire clamp.



Note: Only processes contributing >1 % to the GWP of at least one model are shown.

Figure 3 Global warming potential of 1 unit of 500 W inverter

Results for other impact categories are similar to those observed for GWP in Figure 4, with the exception of non-renewable energy for the reasons discussed in Section 3.1.2. It is worth noting that differences between Pb containing and Pb-free PWB were small for the categories evaluated (e.g., 0.8 % for GWP).

The results presented in Table 8 are similar to those in discussed in Section 3.1.1. The only priority data gap that had not already been identified as a priority based on mass input or GWP is the factory for MIN. As with string inverters, most gaps that a priority based on mass or GWP would also be a priority for other impact categories. This reinforces that, at least for inverters, filling a data gap would be beneficial for categories that might not be of immediate interest.

Table 8 Priority data gaps' impacts for 500 W inverter production (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Logic IC	*0.2*	19.5	18.2	36.0	49.4	23.8	21.6	14.1	9.7	22.5
PWB wo Pb	*NA*	16.1	19.4	14.8	7.8	16.1	16.9	12.1	35.2	17.6
Film capacitor	2.4	7.2	9.5	7.6	5.7	8.0	8.2	5.5	4.9	8.8
Ring core choke inductor	2.5	6.9	6.0	5.5	2.9	7.1	8.0	4.8	4.0	8.1
Capacitor, > 2cm	1.8	5.8	4.5	3.9	5.2	5.6	6.4	4.3	2.7	6.6
Glass diode	*0.3*	5.4	4.9	3.9	2.2	5.3	6.0	4.1	2.3	6.1
Transformer	10.4	3.6	7.5	5.3	3.2	4.6	4.1	2.9	5.0	4.7
Waste paper	*NA*	3.6	*0.1*	*0.1*	*<0.1*	*0.2*	*<0.1*	*<0.1*	*0.4*	*<0.1*
TH transistor	*0.3*	2.9	5.0	3.8	*1.0*	3.6	3.3	2.6	2.2	4.1
Bar extrusion	*NA*	1.7	1.2	1.2	*0.5*	1.4	1.8	1.9	*0.8*	1.8
Ta capacitor	*0.2*	1.5	2.1	1.5	11.5	3.0	1.4	1.7	3.2	3.6
Wire clamp	1.7	1.4	6.0	4.1	*0.7*	2.5	1.5	1.8	4.5	2.1
Waste plastic	*NA*	1.4	*<0.1*	*<0.1*	*<0.1*	*0.2*	*<0.1*	*<0.1*	*0.1*	*<0.1*
Polycarbonate	2.3	*0.9*	*0.6*	*0.5*	1.1	*0.8*	1.1	*0.4*	*0.9*	*0.5*

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Factory	*NA*	*0.3*	*0.3*	*0.2*	*0.1*	*0.4*	*0.2*	*0.5*	8.7	*0.1*

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

3.3. String optimizer

String optimizers are installed with a string inverter to improve overall system performance, drawing from individual panels to maintain output. For previous NIST publications, optimizers were modeled using “Electronics, for control units” from the EI database [29]. Its LCI is available in Ref. [31] and was used here to develop the Representative inventory.

3.3.1. Modeling and data gap identification

The representative and commercial inventories for string optimizers are based on Ref. [32], which minimizes their differences. When building Optimizer #6, transport is included directly and, therefore, market activities are avoided in all cases but HDPE. Similarly to microinverters—Section 3.2.1—EI splits PWB evenly between lead containing and lead free, and then splits again each of these two option between through-hole and surface mounted alternatives. For consistency with previous models, Optimizer #6 was built using only surface mounted lead free PWB.

The six data gaps identified for optimizers are shown in Table 9, all of which were also present in the string inverter as shown in Table 3.

Table 9 Data gaps identified for String optimizer

PWB	Network cable	Cable without plugs
Factory	Cable with plugs	Sheet rolling

3.3.2. Modeling Results

In the following subsections, the magnitude of the data gaps identified in Section 3.3.1 are discussed based on (1) share of material inputs, (2) GWP, and (3) other impact categories. Table 10 reports the results across these three assessments.

Table 10 Data gaps’ impacts for String optimizer (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
PWB SMD w/o Pb	14.8	87.7	83.2	92.0	95.9	88.6	88.6	79.3	41.1	90.4
Factory	*NA*	4.7	8.0	3.8	1.1	4.9	3.4	13.8	48.1	3.6
Network cable	*NA*	1.3	3.9	1.7	*0.8*	1.8	1.2	2.0	3.2	1.4
Ribbon cable w plugs	3.4	*0.7*	1.4	*0.6*	*0.4*	*0.8*	*0.7*	1.1	2.1	*0.6*
Sheet rolling	*NA*	*0.4*	*0.2*	*0.1*	*<0.1*	*0.3*	*0.4*	*0.2*	*0.3*	*0.2*
Cable w/o plugs	*NA*	*0.1*	*0.5*	*0.2*	*0.2*	*0.2*	*0.1*	*0.2*	*0.5*	*0.2*

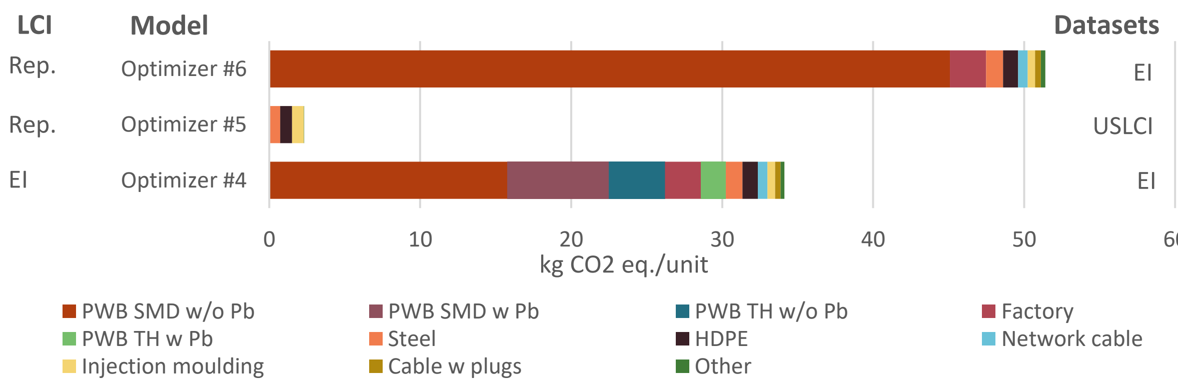
	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
TOTAL	18.2	94.8	97.1	98.47	98.40	96.5	94.3	96.6	95.2	96.4

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

Table 10 shows two priority data gap based on mass, PWB and ribbon cable with plugs, contributing 14.8 % and 3.4 %, respectively. However, as it was the case for the inverters the network cable and the cable without plugs are measured in units of length, which makes quantifying their impact based on mass infeasible.

Figure 4 shows significant differences between the two models built using EI datasets, with the GWP impact of Optimizer #6 40 % greater than that of Optimizer #4. These differences are caused by PWB's use assumptions in each model. These can be analyzed three ways, in increasing order of importance. First, as pointed out in Section 3.2.2, the GWP impact of lead containing SMD PWB is less than 1 % greater than for lead free SMD PWB. Second, the GWP impact of lead containing TH PWB is 2 % greater than that of lead free TH boards. Thus, the key difference is between SMD and TH boards regardless of their lead content. Third, the GWP of SMD boards—used in Optimizer #6—is more than four times higher than the GWP of TH boards.

As for inverters, the differences between models based on the Rep. inventory are mostly caused by data gaps. Optimizer #6's GWP impact is more than 22 times greater than that of Optimizer #5 because data gaps are responsible for almost 95 % of the impact of the former—Table 8. As seen in Figure 4, 88 % of the impact is due to PWB. The factory and network cables are also priority gaps based on GWP impact because they contribute 4.7 % and 1.3 % to the impact of Optimizer #6, respectively.



Only processes contributing >1 % to the GWP of at least one model are shown.

Figure 4 Global warming potential of 1 unit of String optimizer

The difference between SMD and TH PWB can also be observed in other impact categories. Unlike inverters, the absence of aluminum makes the non-renewable energy similar to other impact categories, with Optimizer #5 having a much lower impact than the other impact categories.

As shown in Table 11, there are no data gaps that are a priority based on other impact categories that are not already a priority based on mass or GWP impacts. PWB is the largest contributor to most impact categories, and typically responsible for about 90 % of the impact. The factory is a priority gap for all non-mass categories evaluated, and the network cable is a priority based on all impact categories but ODP. Finally, despite not being a priority based on GWP, cables with plugs are a priority based on three categories besides mass input: AP, RE, and MIN.

Table 11 Priority data gaps' impacts for String optimizer installation (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
PWB SMD w/o Pb	14.8	87.7	83.2	92.0	95.9	88.6	88.6	79.3	41.1	90.4
Factory	*NA*	4.7	8.0	3.8	1.1	4.9	3.4	13.8	48.1	3.6
Network cable	*NA*	1.3	3.9	1.7	*0.8*	1.8	1.2	2.0	3.2	1.4
Cable w plugs	3.4	*0.7*	1.4	*0.6*	*0.4*	*0.8*	*0.7*	1.1	2.1	*0.6*

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

3.4. 3 kWp electric subsystem

The electric installation described in Ref. [21], which is used here as the basis for Rep. is also the basis for EI. It includes all electrical components between the PV panels and the electricity grid excluding the inverter. It contains a fuse box and cables that connect panel frames and mounting structure to the lighting arrester, panels to the inverter, and the inverter to the electric panel. A simpler inventory had been described in Ref. [22, 32] and used for previous NIST research and tools [32].

The installation assumes a 3 kW_P system based on expert knowledge, Ref. [21] indicates most of the material use can be assumed to be proportional to the installed capacity. However, Krebs et al. used 3 units of this installation as part of their 10 kW_P system [20].

3.4.1. Modeling and data gap identification

Despite both representative and commercial inventories being based on Ref. [25] there are important differences in how they are implemented. Rep. directly includes transport while EI include transport through market activities. Rep. includes 17.6 kg of HDPE as input while EI reports 14.41 kg (18.1 % lower). This may be because Rep. is based on Ref. [22]'s "unit process raw data of the electric installation for a 3 kW_P plant" on Table 11.30, and the value reported in EI might have been taken from "Material use for the electric installations" on Table 11.29, whose original source is Ref. [33].

Several waste processes vary across the two inventories. The amount of waste electric wiring is 0.06 kg for Rep. and 29.34 kg for EI, a 489 multiple difference, because EI calculates this value using the sum of copper, HDPE, and nylon while Rep. only consider the "disposal, building, electric wiring, to final disposal" as waste electric wiring. Also related to waste electric wiring, Ref. [22] includes waste plastic from industrial electronics as an approximate sum of HDPE, PVC, Nylon and polycarbonate, 20.2 kg in total. EI however, splits waste plastics into waste PVC—with an amount equal to the PVC input—and waste PE/polypropylene (PP). Waste PE/PP is used as a proxy for the treatment of polycarbonate and epoxy resin and is, therefore, equal to the sum of epoxy and polycarbonate inputs. Finally, EI includes two additional waste outputs: scrap copper—a proxy for the treatment of brass—and scrap steel—equivalent to the sum of steel and zinc inputs. These waste outputs are not present in Ref. [22] and were therefore not included in Rep.. In summary, EI considers the recovery of metal in cables, which is not considered in Rep. because it was not considered in Ref. [22]. The treatment of waste plastic is accounted for differently in both inventories, with Rep. adding them as "waste plastic" and EI including most of their mass under "waste electric wiring." As for previous models, production and treatment processes were chosen whenever possible when building Elec. In. #6. The exception was copper, for which a market activity had to be selected because it could have multiple origins.

In total, eight data gaps were identified while building Elec. In #5, as shown in Table 12.

Table 12 Data gaps identified for 3 kWp electric subsystem

Copper	Nylon 6	Brass	Zinc
Polycarbonate	Wire drawing	Waste plastic	Waste wiring

3.4.2. Modeling Results

In the following subsections, the magnitude of the data gaps identified in Section 3.4.1 are discussed based on (1) share of material inputs, (2) GWP, and (3) other impact categories. Table 13 reports the results across these three assessments.

Table 13 Data gaps' impacts for 3 kW_p electric subsystem (% of total impact)

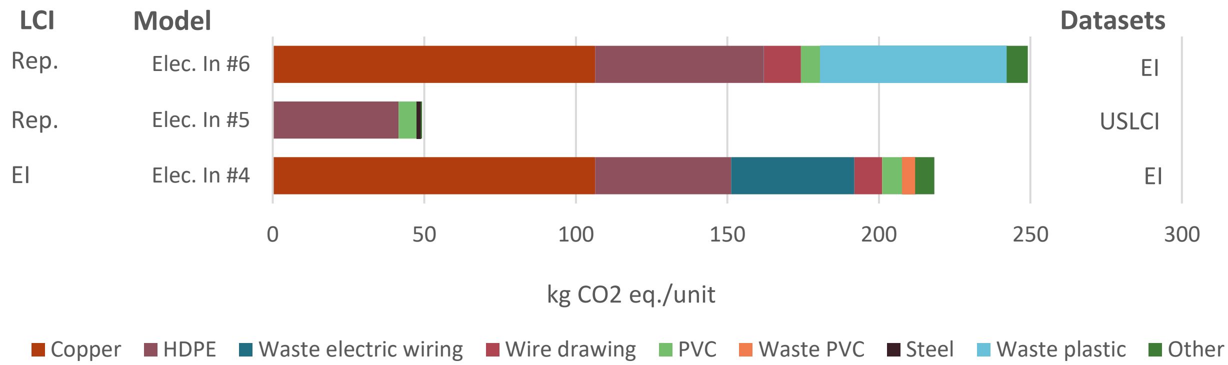
	Mass	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**NON-RE**	**RE**	**MIN**	**WATER**
Copper	29.1	42.7	92.1	92.2	20.9	81.2	48.1	83.7	77.7	83.5
Waste plastic	*NA*	24.7	*0.2*	*0.3*	*0.4*	1.6	*0.4*	*<0.1*	1.5	*<0.1*
Wire drawing	*NA*	4.9	4.1	4.3	2.0	4.8	5.6	5.7	3.8	5.6
Nylon 6	*0.5*	*0.8*	*0.1*	*<0.1*	*<0.1*	*0.4*	*0.8*	*<0.1*	*<0.1*	*<0.1*
Polycarbonate	*0.4*	*0.6*	*<0.1*	*<0.1*	*0.9*	*0.3*	*0.8*	*0.3*	*0.4*	*0.3*
Brass	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Zinc	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Waste electric wiring	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
TOTAL	30.1	73.8	96.7	97.02	24.27	88.4	55.7	89.9	83.5	89.5

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

Table 13 shows that of the eight data gaps, five are material inputs—copper, nylon polycarbonate, brass and zinc. Of these inputs, only copper is a priority data gap, and responsible for more than a quarter of all input mass.

The differences between the representative and commercial inventories, and the subsequent modeling differences are shown in Figure 5. Due to the larger amount of HDPE in Rep. relative to EI, the impact of this input is 24 % higher for Elec. In. #6 than for Elec. In. #4. The impact of the combined treatment for waste electric wiring and PVC is 27 % lower for Elec. In. #4 than the impact of the waste electric wiring and waste plastic in Elec. In. #6.

For models based on Rep., the impact of Elec. In. #6 is about five times higher than that of Elec. In. #5. These differences are primarily due to data gaps, which account for almost three quarters of Elec. In. #6's impact—see Table 10. Based on GWP, the most important of the data gaps is copper, which contributes 43 % of the GWP impact. Waste plastic and wire drawing—contributing 25 % and 5 %, respectively—are also priority data gaps based on this category.



Only processes contributing >1 % to the GWP of at least one model are shown

Figure 5 Global warming potential of 1 unit of 3 kW_p electric subsystem

Differences between Elec. In. # 4 and Elec. In. #6 are not as significant for other impact categories as they were for GWP with two exceptions driven by a single process. Waste electric wiring requires more renewable energy and more mineral resources than its Elec. In. #6 counterpart, making the impact of Elec. In. # 4 higher than Elec. In. #6 for these two impact categories.

Table 14 shows there are no priority data gaps other than those already identified through mass input and GWP. Copper and wire drawing are both priority data gaps in all categories assessed. Waste plastic is a priority based on GWP, POCP, and MIN, with its contribution being less than 2 % for either of the latter two categories.

Table 14 Priority data gaps' impacts for 3 kW_p electric subsystem (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Copper	29.1	42.7	92.1	92.2	20.9	81.2	48.1	83.7	77.7	83.5
Waste plastic	*NA*	24.7	*0.2*	*0.3*	*0.4*	1.6	*0.4*	*<0.1*	1.5	*<0.1*
Wire drawing	*NA*	4.9	4.1	4.3	2.0	4.8	5.6	5.7	3.8	5.6

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

3.5. Slanted roof mounting subsystem

PV systems are typically installed on open ground constructions, on top of roofs (flat or slanted), or integrated into the façade of a building [19]. For this study, the slanted roof mounting subsystem option is selected to align with NIST program and project priorities and follow Ref. [20]. The different systems are similar, but not equivalent. Therefore, data gaps were identified for all mounting systems, but only quantified for systems mounted on a slanted roof. All other options were also modeled and will be made available—see Appendix B

3.5.1. Modeling and data gap identification

Both Rep. and EI for a slanted roof mounting subsystem are based on data from Jungbluth and his collaborators, Rep. onRef. [21] and EI on Ref. [22]. Thus, Rep. and EI are identical except that Rep. includes transport directly in the inventory while EI includes transport as part of market activities. For that reason, as for previous models, market activities were avoided when developing Slanted #6 when feasible. The one exception is the provider for aluminum because it could be primary aluminum or recovered from scrap.

Five data gaps were identified based on the slanted roof mounting system—Table 15. In addition polyurethane and synthetic rubber are data gaps used in slanted roofs integrated construction while wire drawing, zinc coating of pieces, and zinc coating of coils are data gaps used in open ground construction. As in the case of inverters—Section 3.1.1—bar extrusion is a data gap because USLCI does not have this activity separated from the production of extruded aluminum.

Table 15 Data gaps identified for Slanted roof mounting subsystem

Bar extrusion	Sheet rolling	Waste paperboard	Waste PS	Waste PE/PP

3.5.2. Modeling Results

In the following subsections, the magnitude of the data gaps identified in Section 3.5.1 are discussed based on (1) share of material inputs, (2) GWP, and (3) other impact categories. Table 16 reports the results across these three assessments.

Table 16 Data gaps' impacts for Slanted roof mounting subsystem (% of total impact)

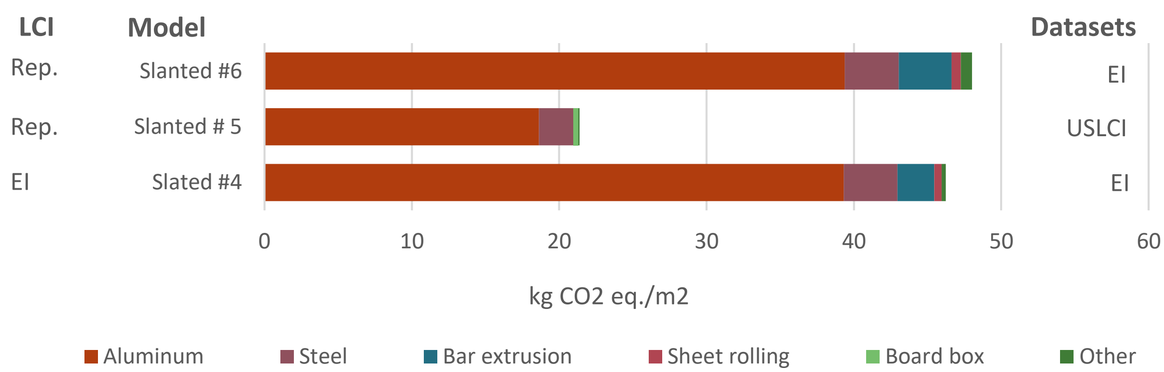
	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Bar extrusion	*NA*	7.5	5.7	8.8	8.7	6.5	8.5	14.2	5.4	8.4
Sheet rolling	*NA*	1.3	*0.9*	1.2	1.5	1.2	1.4	1.0	1.7	*0.9*
Waste paper	*NA*	*0.5*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Waste PS	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Waste PE	*NA*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
TOTAL	*0.0*	9.3	6.6	10.02	10.25	7.7	9.9	15.2	7.1	9.4

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

Table 16 shows there are no material input data gaps because five data gaps identified are either waste treatment processes or processes that alter an existing material input.

Modeling choices caused a 4 % difference between the impacts of Slanted #4 and Slanted #6, despite both models being based on effectively the same inventory—Figure 6. Most significantly, the extrusion process for the Rest of World (RoW) geography used in Slanted #6 has a GWP 43 % higher than the Rest of the European Region (RER) geography used in Slanted #4. Processes individually contributing less than 1 %, grouped as “others” in Figure 6, have almost 3 times more impact in Slanted #6 than in Slanted #4. This is a result of having selected US, global (GLO), or RoW production processes in Slanted #6, and not RER market activities as in Slanted #4.

The difference between the two processes based of Rep. are more significant, with the impact of the model using EI datasets (Slanted #6) being 2.25 times higher than that of the model using USLCI (Slanted #5). Despite the USLCI dataset including extrusion and aluminum production, its GWP impact is 47 % generated by EI’s market activity for aluminum. Steel production in USLCI also has a 36 % lower GWP than its equivalent EI market activity. As shown in Table 16, data gaps are responsible for 9.3 % of Slanted #6’s GWP, but only 1.8 % after removing bar extrusion.



Only processes contributing >1 % to the GWP of at least one model are shown.

Figure 6 Global warming potential of 1 m^2 of Slanted roof mounting subsystem

Other impact categories showed similar results as those from GWP, with the impacts of Slanted #4 and Slanted #6 being relatively similar, and usually higher than those of Slanted #5. The exception is non-renewable energy, due to the effects of aluminum already discussed in Section 3.1.2, and also, to a much lower extent, for renewable energy. This would support the hypothesis that the aluminum production in USLCI uses more electricity than its EI counterpart.

As seen in Table 17, bar extrusion is a priority data gap in all impact categories evaluated. Sheet rolling is a priority data gap for all impact categories except acidification and water use.

Table 17 Priority data gaps' impacts for Slanted roof mounting subsystem (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Bar extrusion	*NA*	7.5	5.7	8.8	8.7	6.5	8.5	14.2	5.4	8.4
Sheet rolling	*NA*	1.3	*0.9*	1.2	1.5	1.2	1.4	1.0	1.7	*0.9*

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

3.6. 10 kW$_P$ single-Si panel slanted roof system

Thus far the focus has been on individual components of a residential PV system. This section models the entire system using the component discussed previously to represent the entire installation of a 10 kW$_P$ single-Si slanted rooftop system: panels, inverter(s), electric installation and roof mounting installation.

3.6.1. Modeling and data gap identification

Rep. is taken from Ref. [20], substituting their multi-Si panel with an efficiency of 16.5 % for a single-Si panel with an efficiency of 18.0 % [19], and reducing the area of the panel accordingly. In addition to the components mentioned above, this inventory also includes transport of the components to the construction site and use of electricity for the construction equipment. A similar inventory is available for the commercial database for a 3 kW$_P$ system, which was scaled by a factor of 3.33 to build System #4 to facilitate its comparison with the models based on Rep. (System #5 and System #6). The other difference between the representative and the commercial inventories is that the latter does not explicitly include transport.

Because the model based on Rep. built using USLCI processes (System #6) uses the single-Si panel developed in Ref. [18] and the string inverter, electric installation, and slanted roof mounting system developed as part of this report, no data gaps were identified for this installation.

3.6.2. Modeling Results

Figure 7 shows that the GWP impact of System #4 is 86 % higher than that of System #6, both of which are built using EI datasets. There are two reasons for these differences. First, the GWP impact of Single-Si Panel #4 was 2.4 times greater than that of Single Si Panel #6 discussed in Ref. [18]. Second, the efficiency of the panels used in simple scaling of System #4 is 14 % [21, 22], which means System #4 requires 28 % more panel area than System #6. Similar trends between these two models are observed for other impact categories.

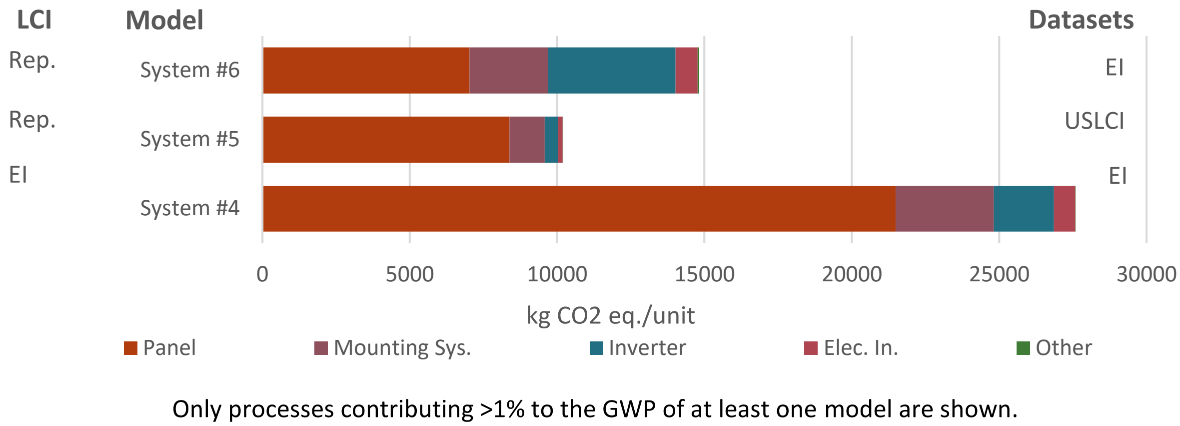


Figure 7 Global warming potential of 1 unit of 10 kWP single-Si panel slanted roof system

More relevant to this study are the differences between System #5 and System #6, as the former's GWP impact is 48 % higher than the latter. As already discussed in this report, these differences are partially caused by data gaps in the production of inverter, electrical installation, and mounting system. Another source for the differences is the 37 % higher GWP impact of the panel used in System #6 relative to those used in System #5 as shown in Ref. [18].

The preponderance of the panel, responsible for 47 % of System #6's GWP, had already been reported in Krebs et al. [20]. Although the panel is the main contributor to all the impact categories evaluated, its importance—and that of all other components—varies with each impact category. For example, the inverter is usually the second main source of impact, but its contribution ranges between less than 7 % (WATER) to 34 % (EP). Although data gaps in some of the components evaluated are likely to be important for the whole system, whether they are a priority will depend on the category of interest even more than when these components were evaluated individually.

3.7. Recycling of silicon panel

Although PV panel pane glass recycling is not mandatory, there were 38 recyclers as of 2024 that can treat a variety of silicon and non-silicon based PV panels [34]. Additionally, PV panel manufacturers have introduced PV panel recycling programs and the Solar Energy Industries Association (SEIA) founded the National PV Recycling Program in 2016, providing a recycling network for their members [35].

3.7.1. Modeling and data gap identification

Frischknecht et al. (2020) included a model based on Ref. [36, 37] for the recycling of silicon-based modules in which aluminum frames and junction boxes are manually dismantled While modules are crushed and its components are separated to recover "up to 80 % of the panel" [19, 38]. This model is used as Rep. even though it is based on a European recycling plant because none of the recycling processes for silicon panels in Ref. [40] were available for U.S. plants.

Rep. follows the end-of-life approach, in which treatment efforts and emissions are fully attributed to the treatment service [19]. However, the three recovered materials: aluminum, copper, and glass cullet have been added as outputs. Thus, it is possible to allocate impacts to the recovered materials. The revenues from selling these recovered materials were also added, to allow for economic allocation. No EI inventory was identified for panel recycling. Therefore, there is no RECYCLING #4 model.

Two data gaps were identified while building RECYCLING #5, both related to the treatment of waste plastic: incineration and sanitary landfill.

3.7.2. Modeling Results

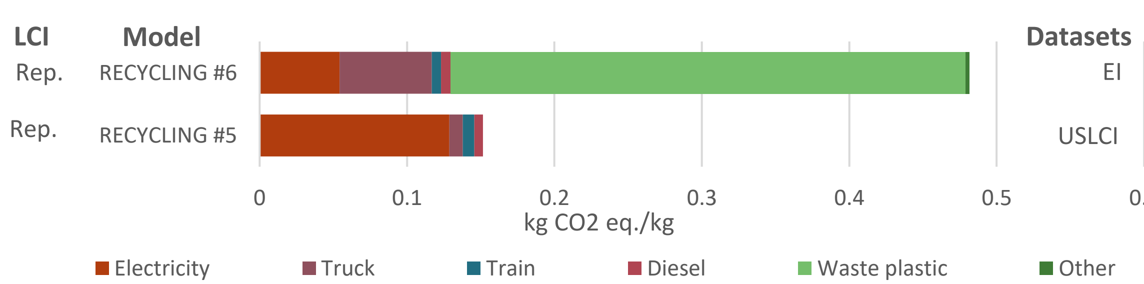
In the following subsections, the magnitude of the data gaps identified in Section 3.7 are discussed based on (1) share of material inputs, (2) GWP, and (3) other impact categories. Table 18 reports the results across these three assessments.

Table 18 Data gaps' impacts for Recycling of silicon panel (% of total impact)

	Mass	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Incineration	*NA*	72.6	13.2	5.0	8.2	15.5	3.8	2.4	5.2	3.8
Landfill	*NA*	*0.5*	*0.4*	74.7	*0.5*	*0.4*	*0.2*	*<0.1*	5.8	*0.2*
TOTAL	*NA*	73.1	13.6	79.66	8.70	15.9	4.0	2.5	10.9	4.0

Note: Italicized values indicate the data gap would not be a priority for that category. ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

There are no material input data gaps—Table 17—because both data gaps identified in Section 3.7.1 are waste flows. The GWP impact of Recycling #6 is more than three times higher than that of Recycling #5. The greatest difference between both models are the data gaps identified above: incineration and landfilling of waste plastic. In Figure 8 both processes are combined as "Waste plastic" and Table 17 shows that more than 99 % of the GWP impact of the data gaps is due to incineration. Another important difference between both models is the impact of truck transport, which is almost seven times higher in EI (Recycling #6) than in USLCI (Recycling #5). This last difference is ameliorated by the impact of electricity, which is 2.3 times higher in Recycling #5 than in Recycling #6 due to differences in their respective datasets as discussed in Ref. [17].



Only processes contributing >1 % to the GWP of at least one model are shown.

Figure 8 Global warming potential of 1 kg of Recycling of silicon panel

Contrary to other models, there are important differences between the impacts of these models. This is partially a result of the kind of model evaluated: with fewer and simpler items (exchanges) than most of the others evaluated: two waste treatment processes, two transport activities, and two energy sources. This results in different exchanges being the largest contributor to different impact categories. For Recycling #6, waste plastic treatment remains the main source of impact based on EP due to landfilling—Table 18. Truck transport is the main contributor to the remaining ISO 21930 mandatory impact categories. For all these categories, Recycling #6 has a higher impact than Recycling #5 (except for ODP) as electricity use for Recycling #6 has an impact 5.3 times greater than for Recycling #5. For the FEDEFL Inventory indicators, truck and electricity are more important contributors than waste treatment. In addition, the only category for which Recycling #5 has a higher impact than Recycling #6, is Water resources because the impact of USLCI electricity for this category is more than 11 times higher than of EI electricity.

The impacts of the recycling process, though small, are not negligible in most impact categories evaluated. Assuming a 13.145 kg/m^2 framed panel as in Ref. [19], recycling may add between 0.2 % (ODP) and 5.3 % (GWP) to the impact of the panel—Table 19.

Table 19 Additional impact of the recycling to the production of a panel (%)

	GWP	AP	EP	ODP	POCP	NON-RE	RE	MIN	WATER
Additional impact	5.3	1.4	2.0	0.2	2.6	0.8	0.7	3.9	4.9

ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER).

As shown on Table 19, waste incineration is a priority data gap in all impact categories. Waste plastic landfilling is only a priority data gap based on mineral resources depletion and EP.

4. Additional analyses

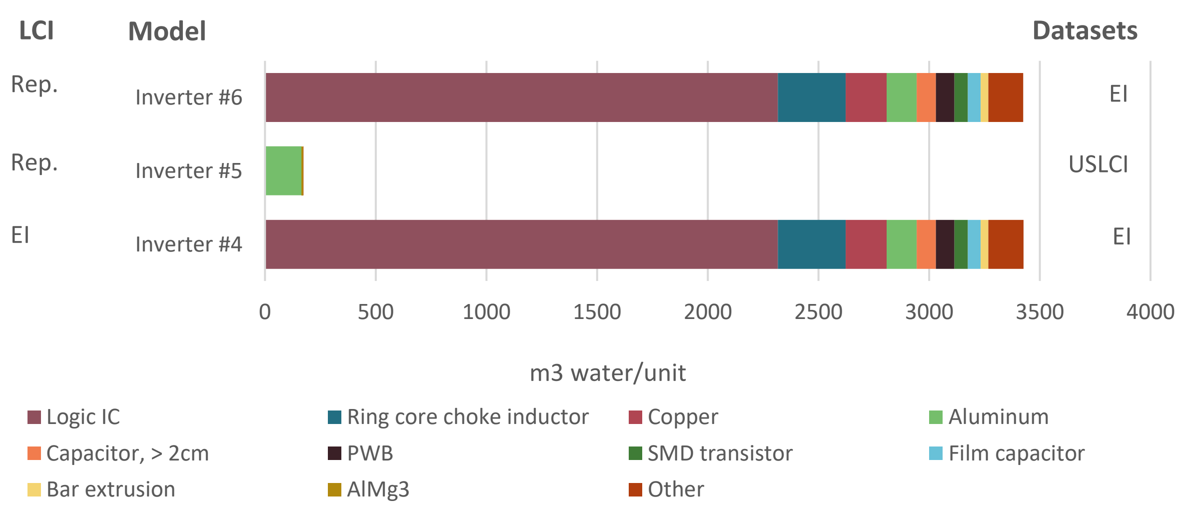
In this section, two additional analyses are included. First, a comparison between the impact assessment methods used for resources in Ref. [18] and FEDEFL Indicators was made to assess whether the latter could be used instead of the former. Second, a system level analysis analogous to the one conducted at the panel level in Ref. [18] was completed to rank priority data gaps at the highest level of aggregation.

4.1. ReCiPe 2016 resource categories and CED vs FEDEFL inventory results

In Ref. [18], indicators that were not mandatory according to ISO 21930 [14] were modeled using ReCiPe 2016 and CED [14, 25–28]. It was suggested there that similar resource-related indicators could be found in the FEDEFL Inventory Methods if fossil fuel depletion was not an indicator of interest [24]. This suggestion is qualitatively tested here by comparing the results from FEDEFL Inventory Indicators and its related categories in the aforementioned Life Cycle Impact Assessment (LCIA) methodologies. This is done for both the inverter and the slanted roof mounting systems. These two products were selected because of their differences in the number of inputs and data gaps and because they are qualitatively different types of products. In this case, inverters represent the more technological aspect of a building system while the mounting system more closely aligns with construction activities and materials.

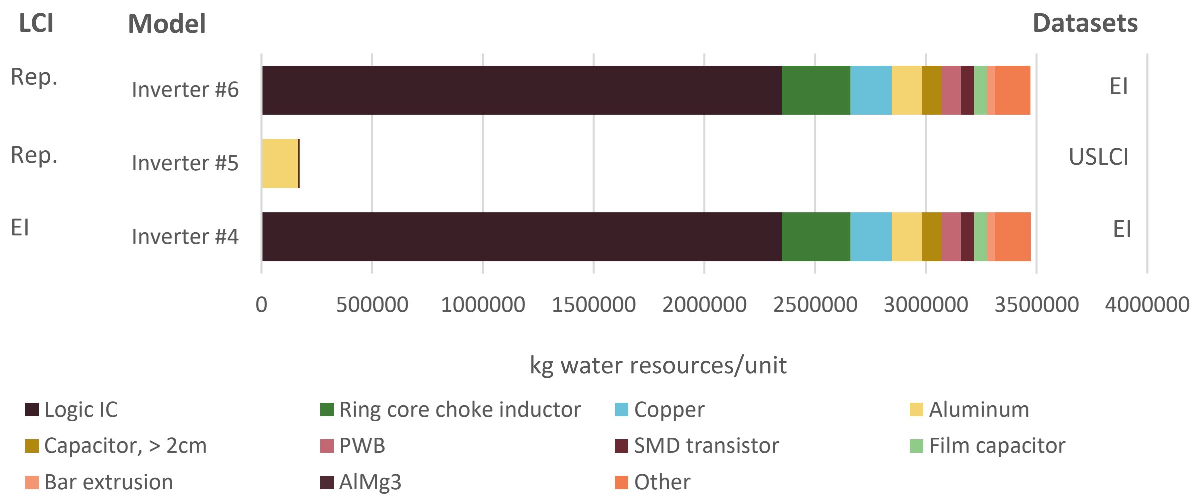
4.1.1. Water

The results of both water impact categories are similar for the two systems components evaluated. The WCP for the inverter models—Figure 9—is about 1 % less than its water resources equivalent—Figure 10—after assuming a density of 1000 kg/m^3 (62.43 lb/ft^3). Values for individual processes contributions follow this trend, with the values for the FEDEFL Inventory Indicators' category being 1 % to 2 % higher than for ReCiPe. Only in the case of the "Others" group for Inverter #5, the FEDEFL results were 23 % higher than ReCiPe.



Only processes contributing >1% to the WCP of at least one model are shown.

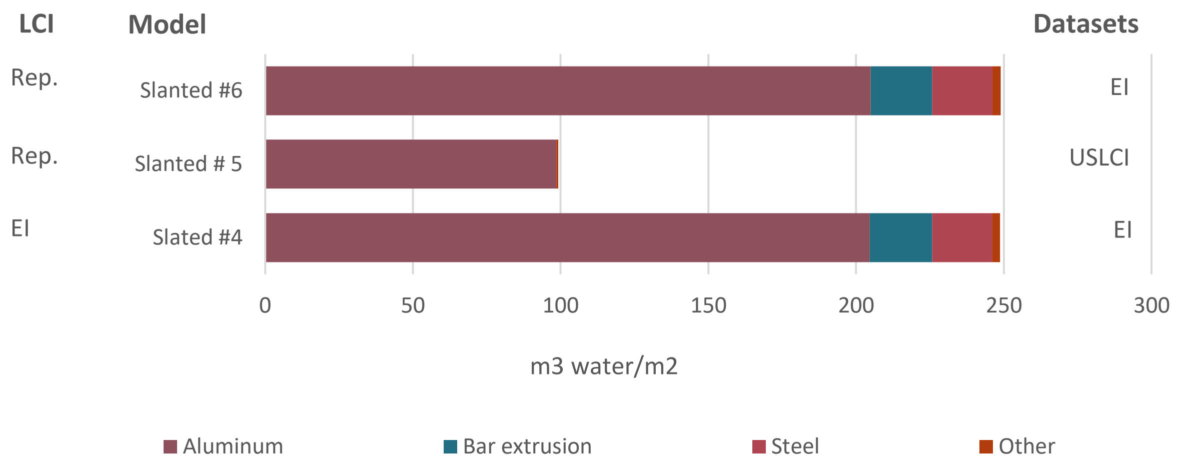
Figure 9 Water use (ReCiPe 2016) of 1 unit of 2.5 kW inverter



Only processes contributing >1% to the use of water resources of at least one model are shown.

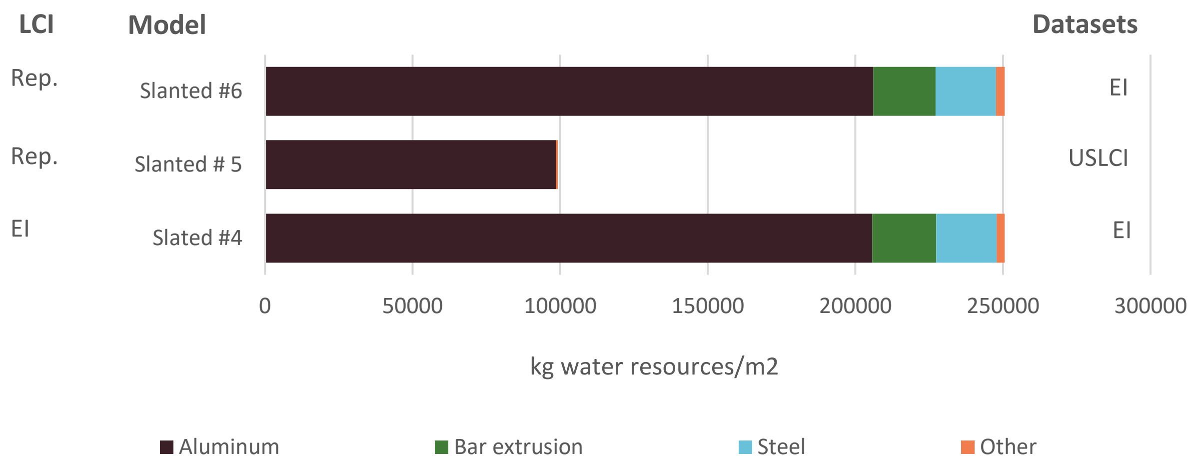
Figure 10 Water resources (FEDEFL Inventory Indicator) of 1 unit of 2.5 kW inverter

The results for the slanted roof mounting system followed the same trend as those from the inverter, with WCP total values—Figure 11—being 1 % lower than those for FEDEFL water resources—Figure 12. The values of the individual contributors are also 1 % to 2 % higher with the FEDEFL indicator, although in this case, the FEDEFL impact of the “Others” group for Inverter #5 is only 3% higher than that using the ReCiPe impact.



Only processes contributing >1 % to the WCP of at least one model are shown.

Figure 11 Water use (ReCiPe 2016) of 1 m^2 of Slanted roof mounting subsystem



Only processes contributing >1 % to the use of water resources of at least one model are shown.

Figure 12 Water resources (FEDEFL Inventory Indicator) of 1 m^2 of Slanted roof mounting subsystem

Therefore, based on the results of these two systems, it is concluded both methods can be used indistinctively for the evaluation of water resources, in those circumstances where a 1 % to 2 % difference is not considered critical.

4.1.2. Mineral resources

For mineral resources, the ReCiPe results for the inverter—Figure 13—are different than those for the FEDEFL Inventory Indicator—Figure 14. The same can be said for the slanted roof—Figure 15 and Figure 16. There are two reasons for these differences. The first is driven by methodological differences. The FEDEFL indicator accounts for the use of mineral resources (e.g., 1 kg of gold is as “impactful” as 1 kg of tin) while the ReCiPe methodology “ranks” the importance of each resource using characterization factors (CFs). The second reason for the observed differences is related to the datasets. As discussed in previous sections (e.g., Section 3.1.2) certain impacts are orders of magnitude higher for the production of aluminum using a USLCI dataset when compared to an EI dataset due to the larger amount of uranium assumed to be required. Because this is a very valuable mineral resource—25.22 kg Cu eq./kg U—the impacts of Inverter #5 and Slanted #5 are much higher than that of the other models, which might obfuscate greater similarities between both indicators for Inverter #4 versus Inverter #6, and Slanted #4 versus Slanted #6.

Figure 13 Minera resource scarcity (ReCiPe 2016) of 1 unit of 2.5 kW inverter

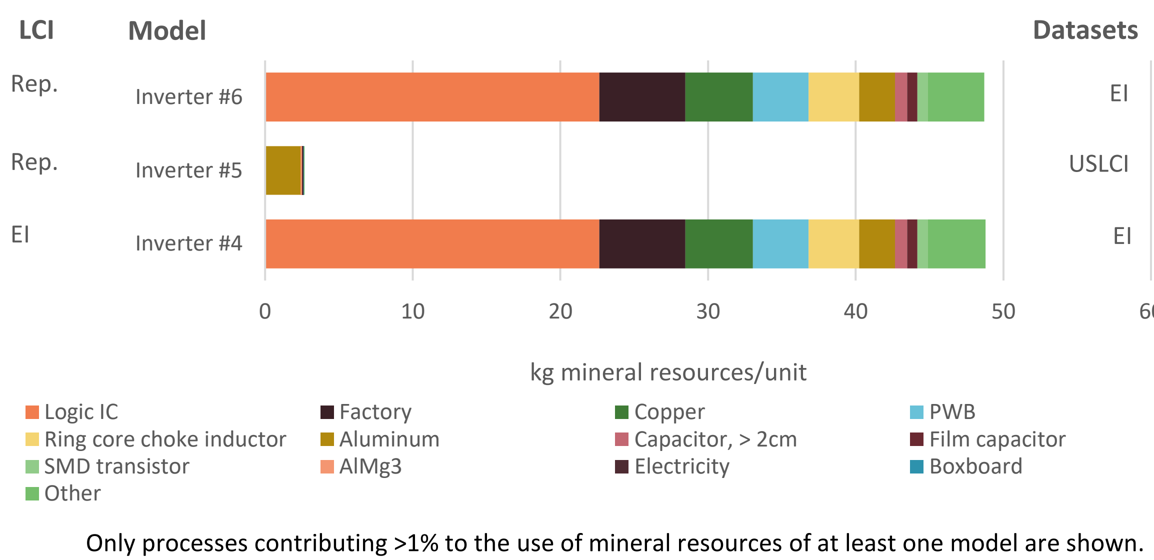
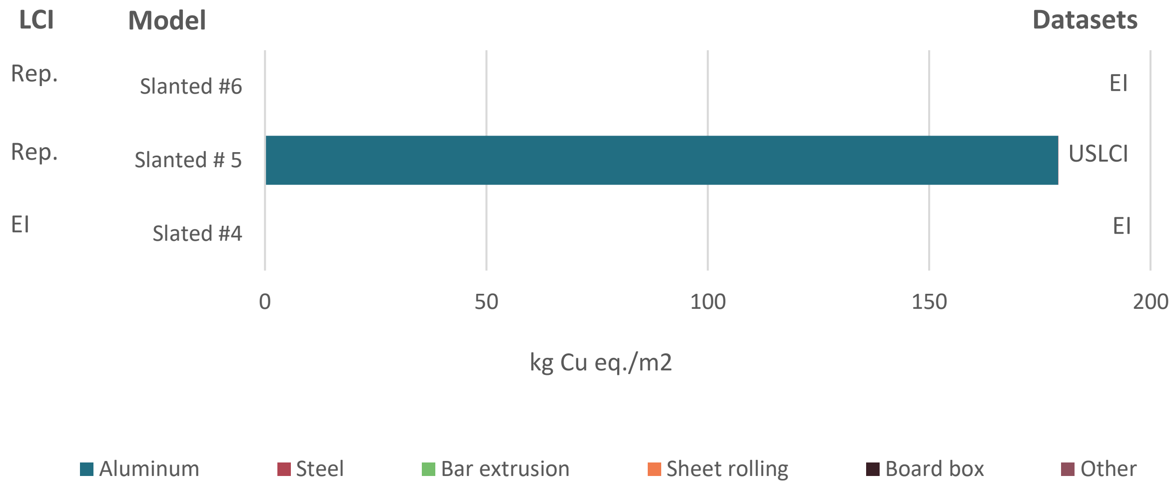
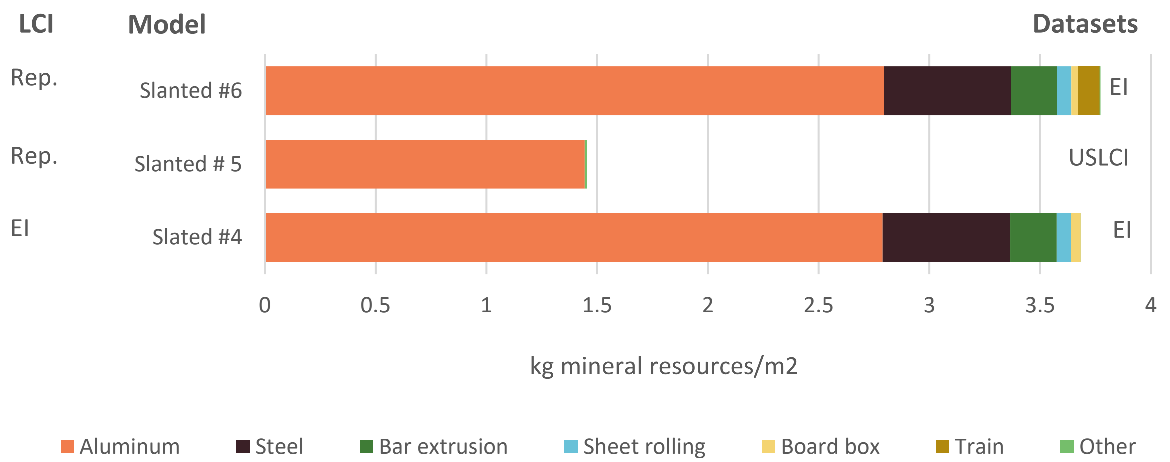


Figure 14 Mineral resources (FEDEFL Inventory Indicator) of 1 unit of 2.5 kW inverter



Only processes contributing >1 % to the SOP of at least one model are shown.

Figure 15 Minera resource scarcity (ReCiPe 2016) of 1 m^2 of Slanted roof mounting subsystem



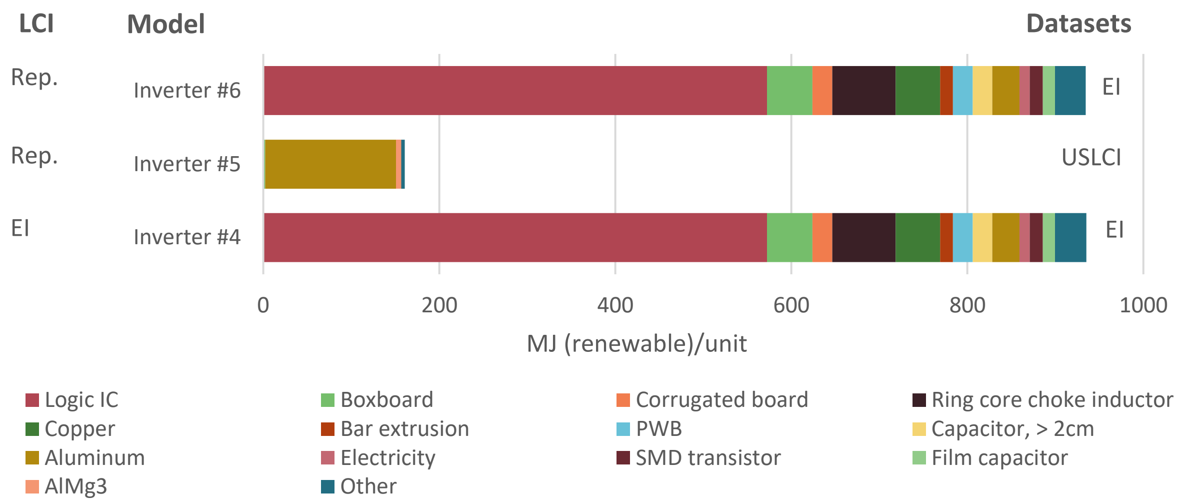
Only processes contributing >1 % to the use of mineral resources of at least one model are shown.

Figure 16 Mineral resources (FEDEFL Inventory Indicator) of 1 m^2 of Slanted roof mounting subsystem

Based on the results of these two systems, it is concluded both methods cannot be used indistinctively for the evaluation of mineral resources. Its use with models built with EI datasets may be more consistent that for models built with USLCI datasets. However, the methodological differences between the two indicators will remain regardless of the database selected.

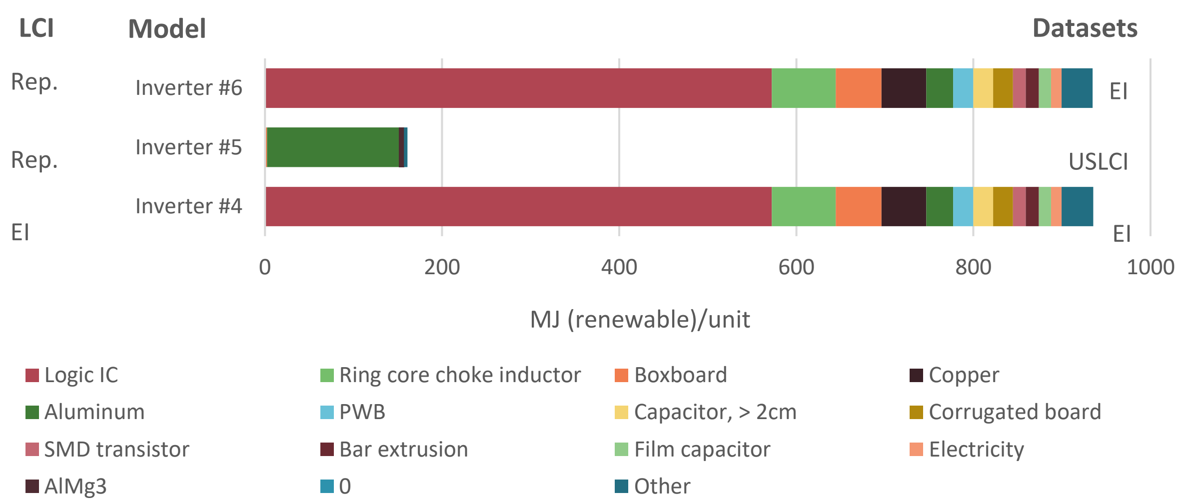
4.1.3. Renewable energy

For renewable energy, the total impact for the three inverter models are identical for both the ReCiPe—Figure 17—and the FEDEFL indicator—Figure 18. The contributions of the different exchanges to both indicators are also identical. The same can be said for the slanted roof mounting systems—Figure 19 and Figure 20. Based on the results of these two systems. It is likely both indicators are identical and can be used indistinctively to assess the use of renewable energy.



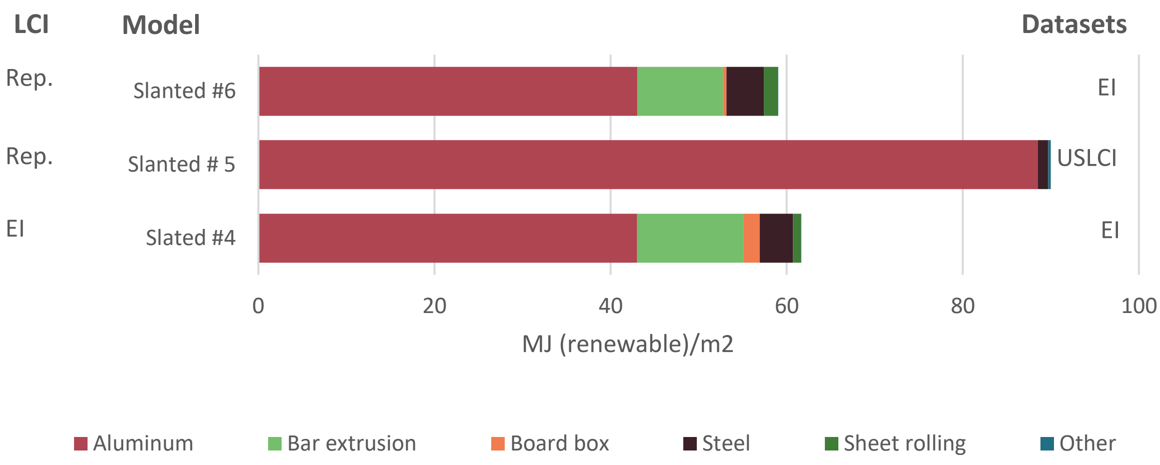
Only processes contributing >1% to the CED_R of at least one model are shown.

Figure 17 Renewable cumulative energy demand (CED_R) of 1 unit of 2.5 kW inverter



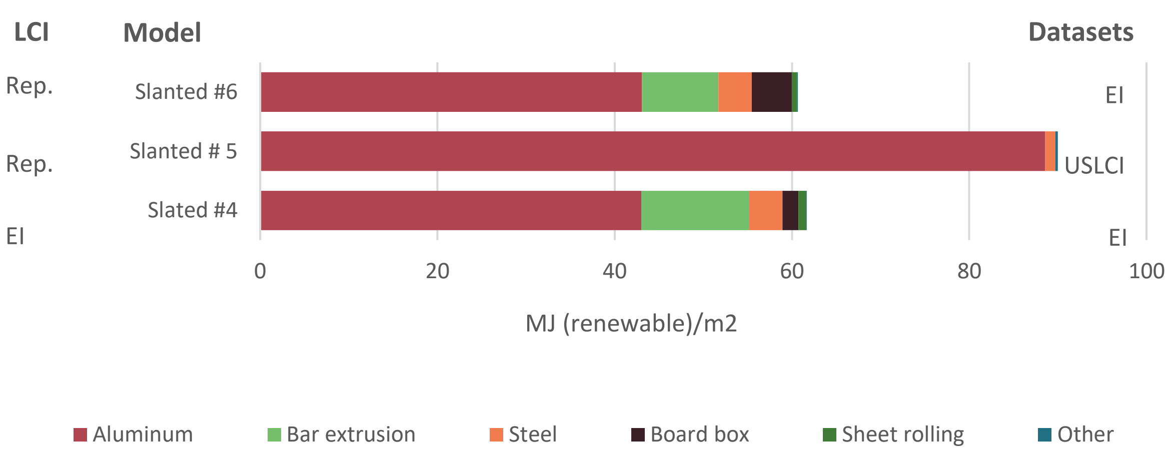
Only processes contributing >1% to the use of non-renewable energy of at least one model are shown.

Figure 18 Renewable energy (FEDEFL Inventory Indicator) of 1 unit of 2.5 kW inverter



Only processes contributing >1 % to the CED$_R$ of at least one model are shown.

Figure 19 Renewable cumulative energy demand (CED$_R$) of 1 m^2 of Slanted roof mounting subsystem

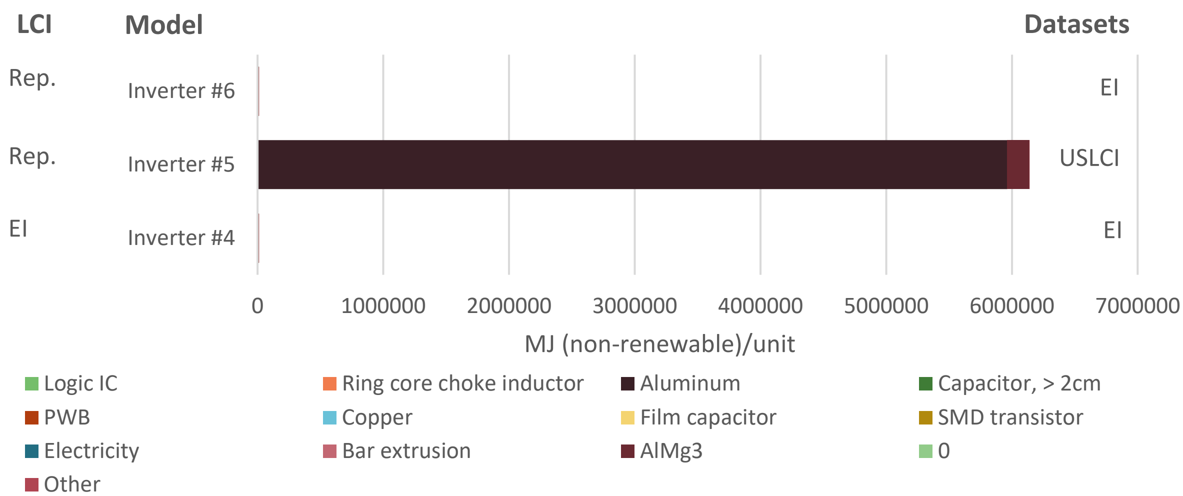


Only processes contributing >1 % to the use of renewable energy of at least one model are shown.

Figure 20 Renewable energy (FEDEFL Inventory Indicator) of 1 m^2 of Slanted roof mounting subsystem

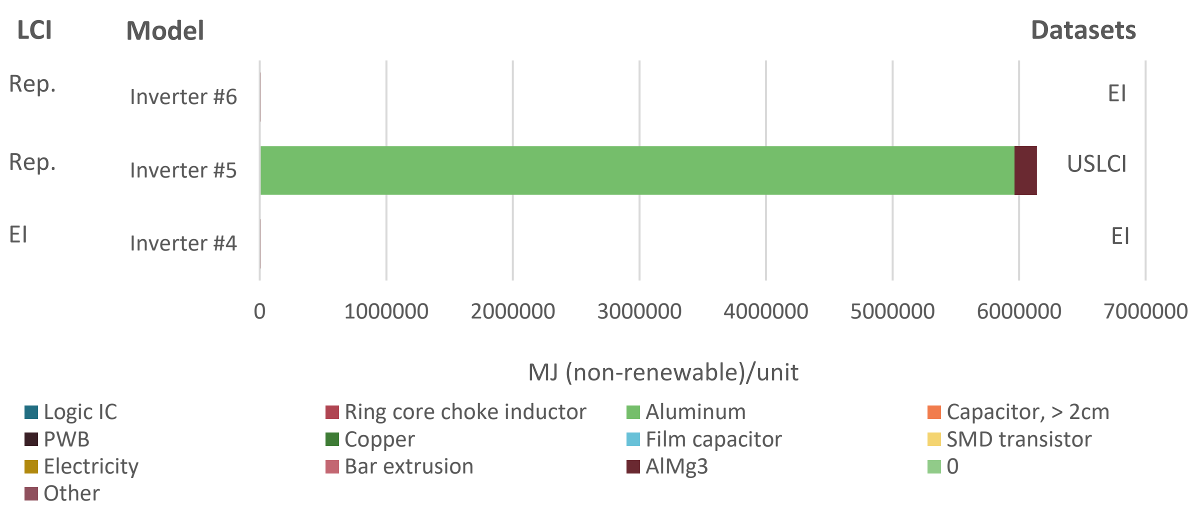
4.1.4. Non-renewable energy

For non-renewable energy, the total impact for the three inverter models is identical for both the ReCiPe—Figure 21—and the FEDEFL indicator—Figure 22. The contributions of the different exchanges to both indicators are also identical. The same can be said for the slanted roof mounting systems—Figure 23 and Figure 24. Based on the results of these two systems. It is likely both indicators are identical, and therefore can be used indistinctively to assess the use of renewable energy.



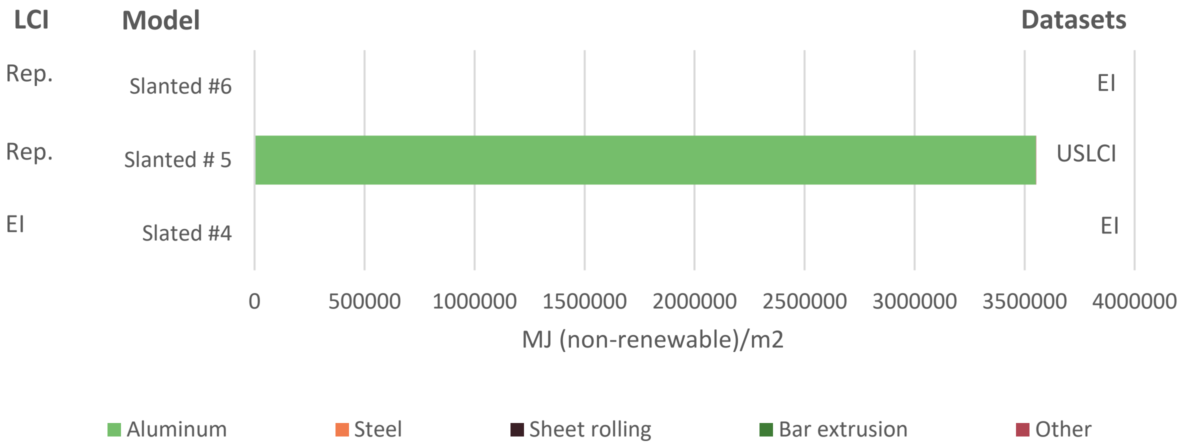
Only processes contributing >1% to the CED_{NR} of at least one model are shown.

Figure 21 Non-renewable cumulative energy demand (CED_{NR}) of 1 unit of 2.5 kW inverter



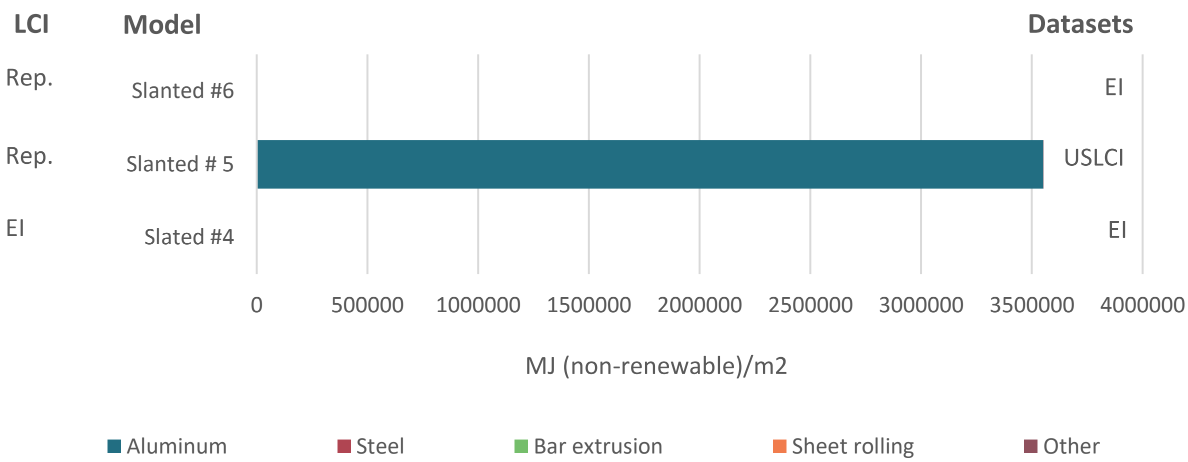
Only processes contributing >1% to the use of non-renewable energy of at least one model are shown.

Figure 22 Non-renewable energy (FEDEFL Inventory Indicator) of 1 unit of 2.5 kW inverter



Only processes contributing >1 % to the CED_{NR} of at least one model are shown.

Figure 23 Non-renewable cumulative energy demand (CED_{NR}) of 1 m^2 of Slanted roof mounting subsystem

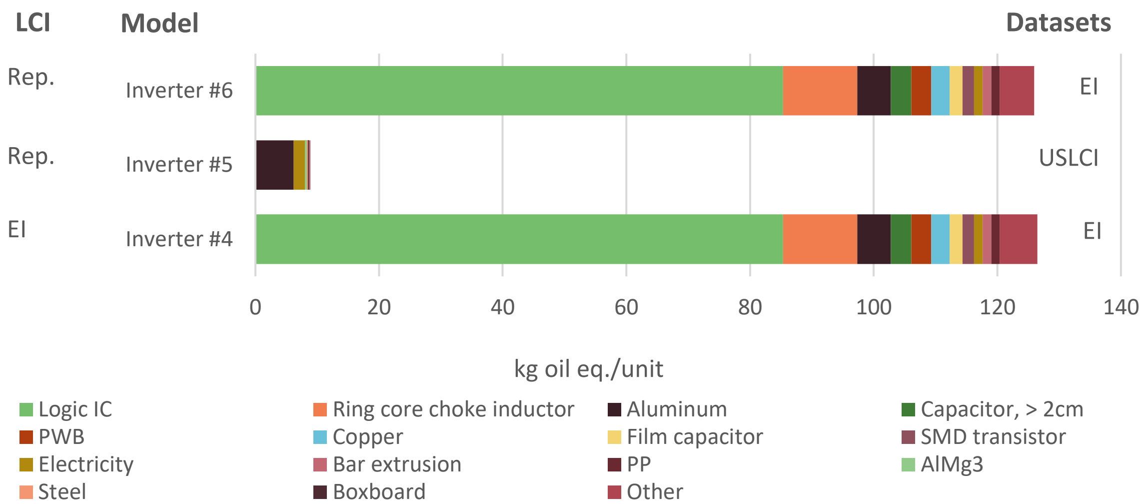


Only processes contributing >1 % to the use of non-renewable energy of at least one model are shown.

Figure 24 Non-renewable energy (FEDEFL Inventory Indicator) of 1 m^2 of Slanted roof mounting subsystem

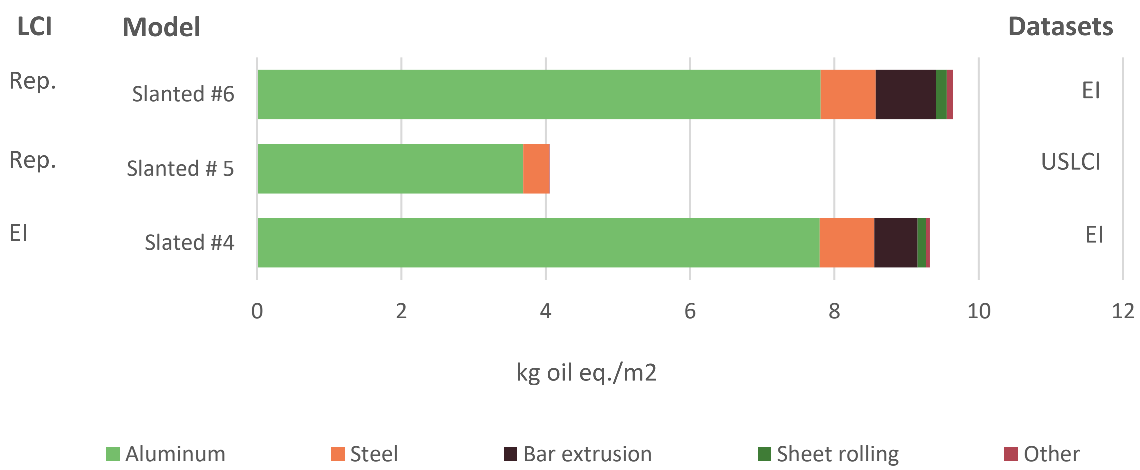
4.1.5. Fossil fuel

Due to the large amount of non-renewable energy used in the production of aluminum for both Inverter #5 and Slanted #5 in Section 4.1.4, those results do not look similar to those for fossil resource scarcity—Figure 25 and Figure 26. Although both indicators—use of non-renewable energy and fossil resource scarcity—are not conceptually the same, they are related. This relationship can be seen in the similar relative contributions exchanges have on both indicators. For Inverter #4 and Inverter #6, the largest discrepancy is that the relative contribution of electricity is 8% higher for non-renewable energy use than for fossil resource depletion. For Inverter #5, the contribution of Aluminum is 33 % higher for non-renewable energy use than for fossil resource depletion. These differences are a result of nuclear being a non-renewable energy source not based on fossil fuels. For Slanted #4 and Slanted #6, the largest difference is a 25 % lower contribution of the "others" group based on non-renewable energy than in fossil resource scarcity. For Slanted #5, the largest difference is a 9 % higher contribution to non-renewable energy use than to fossil resource scarcity.



Only processes contributing >1% to the FFP de of at least one model are shown.

Figure 25 Fossil resource scarcity (ReCiPe 2016) of 1 unit of 2.5 kW inverter



Only processes contributing >1 % to FFP of at least one model are shown.

Figure 26 Fossil resource scarcity (ReCiPe 2016) of 1 m^2 of Slanted roof mounting subsystem

Based on the results of these two systems, it is not recommended to use non-renewable energy use as a proxy for fossil resource scarcity unless the purpose is to give a rough approximation of where fossil fuels are consumed. The reason for that is that fossil resource depletion does not include nuclear fuel. Therefore, the correlation between both indicators will be dependent on the quantity of electricity and the fraction of nuclear in the electricity fuel mix, with an increase on either diminishing the correlation.

4.2. Discussion at the system level

Similar to what was completed in Ref. [18] at the panel level, it is possible to reevaluate the importance of the data gaps evaluated at the end product level (PV system). As an example, Figure 27 shows that most of the GWP generated by the whole system comes from the panel (47 %). However, the data gaps that contribute the most are those from the inverter (27 %). In total, the 56 unique data gaps are responsible for 41 % of the GWP impact of the whole system. Note that these does not include the data gaps discussed in Ref. [18] regarding the initial steps up the manufacturing supply chain of the panel (e.g., solar grade silicon, wafer, etc.).

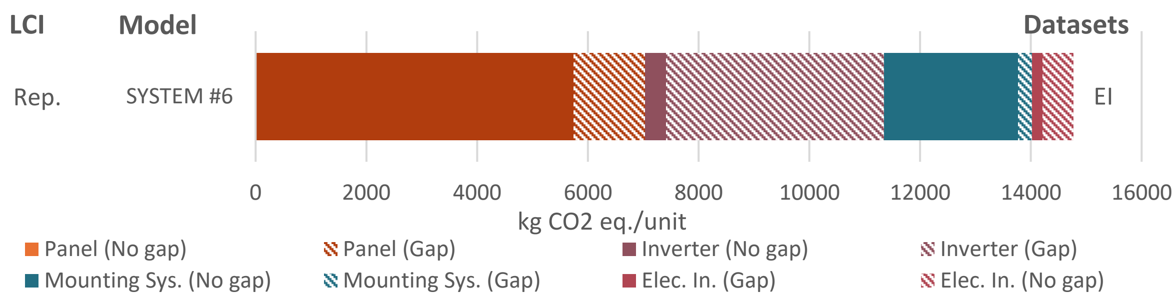


Figure 27 GWP of the production of a 10 kW$_P$ system, broken by component and gaps/no gaps

Table 20 presents those components contributing more than 1 % to the GWP of the whole system. These six data gaps are responsible for almost a third of the GWP impact and, therefore, are of particular importance if this impact category is of interest. The data gap contributing the most impact is the logic IC in the inverter (20 %). Solar glass, which was the largest contributor to the GWP impact of the panel in Ref. [18], only contributes 4 % to the impact of the whole system. Despite not appearing on Table 20, it is estimated that tap water would contribute more than 2 % to the GWP impact of the whole system based on the results presented in Ref. [18]. The one other item from Ref. [18], dipropylene glycol monomethyl ether (DPGME), contributes more that 1 %.

Table 20 Data gaps contributing more than 1 % to the GWP of a 10 kW$_P$ PV system

	% Contribution	Component
Logic IC	19.7	Inverter
Solar glass	3.8	Panel
Copper	3.2	Panel, Inverter, Electrical sub-system
Ring core choke inductor	2.6	Inverter
EVA	1.5	Panel
Waste plastic	4.3	Panel, Electric system
TOTAL	32.0	

The components listed above are excellent candidates for prioritization if GWP is of interest. The list of priority data gaps on Table 20 is shorter than that found in Ref. [18] for the panel, yet responsible for 78 % of the impact caused by all data gaps. In addition, filling these data gaps would have benefits in other sectors: Logic IC in electronics and copper and plastic waste in a variety of sectors.

5. Conclusions and future work

This study follows the framework for the identification and quantification of public data gaps developed and applied to construction materials in NIST Technical Note 2338 and expanded in and applied to a building system component (photovoltaic panels) NIST Technical Note 2350 [18]. This study expands on these efforts through several key efforts, the results of which are summarized below.

5.1. Identified data gaps and prioritization

This study is focused on identifying and quantifying the impact of public LCA data gaps of the components of an entire building system (a rooftop residential photovoltaic system) and providing qualitative rankings of data gaps both within each stage of the production supply chain and for the entire assembled system. This study identified and evaluated data gap importance based on their contribution to different impact categories. Data availability and/or ease of filling those gaps is not considered.

Table 22 summarizes the findings of this report and Ref. [18]. In total, 129 non-unique data gaps where identified (i.e., several data gaps appear in multiple components of the PV system or stages in the production supply chain of PV panels), 50 % of which are a priority for at least one of the impact categories assessed. Most data gaps, priority or not, are found in the more complex subsystems: PV panel and inverter. These two are also the two largest sources of GWP, as shown in Section 4.2.

Table 21 Identified data gaps

Component	**Data gaps (#)**	**Priority data gaps (#)**
Panel	22 direct / 49 total	9 direct / 29 total
String inverter	35	10
Microinverter	24	15
String optimizer	6	4
Electric subsystem	8	3
Mounting subsystem	5	2
Recycling	2	2
Non-unique total	102 direct / 129 total	45 direct / 65 total

Of the 36 priority data gaps identified in this study, 23 are unique, as several appear in multiple components—

Table 22. Often, a priority data gap appears on both kinds of inverters and/or the optimizer because the first two components are relatively similar and the latter is also an electronic component. However, a few data gaps (e.g., copper, bar extrusion, wire drawing, and waste plastic) are also a priority for electric or mounting subsystems. In addition, most priority data gaps are a priority for many, if not most impact categories. Therefore, in most instances filling any given priority data gap is going to significantly diminish the contribution of data gaps across impact categories and components.

Table 22 Priority data gaps by component, impact category, and potential

Data gap	Component	Priority for Impact Categories
Logic IC	Inverters	All but mass
Ring core choke inductor	Inverters	All
Capacitor, > 2cm	Inverters	All but mass
PWB	Inverters, string optimizer	All but mass/All[1]
Copper	String inverter and electric subsystem	All but ODP/All[2]
Film capacitor	Inverters	All but mass and ODP
SMD transistor	String inverter	All but mass and ODP
Bar extrusion	Inverters, mounting subsystem	GWP, NON-RE, RE, WATER/All but mass[3]
Factory	Inverters, string optimizer	MIN/All[1]
Wire drawing	String inverter and electric subsystem	AP/All[2]
Glass diode	Microinverter	All but mass
Transformer	Microinverter	All
Waste paper	Microinverter	GWP
TH transistor	Microinverter	All but mass
Ta capacitor	Microinverter	All but mass
Wire clamp	Microinverter	All
Waste plastic	Microinverter and electric subsystem	GWP/GWP, POCP, and MIN[2]
Polycarbonate	Microinverter	Mass, OD, and NON-RE
Network cable	String optimizer	All but mass and ODP
Cable with plugs	String optimizer	Mass, AP, RE, MIN
Sheet rolling	Mounting subsystem	All but AP and WATER
Incineration	Recycling	All
Landfill	Recycling	EP and MIN

ISO 29130 mandatory impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP). Resource indicators: non-renewable energy (NON-RE), renewable energy (RE), mineral resources (MIN), water resources (WATER). Data gaps are a priority for the categories listed for all components unless stated otherwise. The following superscript applies to all the categories after the slash: [1]String optimizer, [2]Electric subsystem, and [3]Mounting subsystem.

In all tables in Section 3, data gaps are ranked according to their GWP impact. Therefore, for each individual component, those tables can be read as a priority list if this category is of particular interest. Workbooks presented on Appendix B can be used to easily rank data gaps for an individual component for other impact categories. A whole-system prioritization was conducted in Section 4.2 based on GWP impact, with the logic IC from the string inverter appearing as the single most impactful data gap. Similar rankings can be conducted for other impact categories using the workbooks on Appendix B.

Priority data gaps whose LCI are publicly available may be the best to start filling, but there may also be a benefit in filling non-priority data gaps when the effort required to do so is limited. Through the development of this data gap analysis, sources to fill some gaps have been identified. What follows does not constitute an exhaustive list, and sources have not been evaluated in terms of quality or complexity. It should be seen as a suggested starting point towards more complete models for PV and related industries in the FLCAC. Ref. [30] cited an Ecoinvent 2 report as sources regarding some of the data gaps identified in this study—Table 23. Note that these reports are from the late 2000's, often based on older data, and representative for Switzerland and other parts of Europe.

Table 23 LCIs for data gaps available in Ecoinvent 2 reports [39]

	Component	Priority for Impact Categories
PWB (all)	String inverters, microinverters, optimizer	All but mass
Computer cable without plugs	String inverters, optimizer	None
Ribbon cable with plugs	String inverters, optimizer	AP, RE, MIN
Plug	String inverters, optimizer	None
Network cable	Optimizer	All but mass and ODP
Factory	Optimizer	All but mass

Note: acidification potential (AP), ozone depletion potential (ODP), renewable energy (RE), mineral resources (MIN)

5.2. LCIA Method Comparisons

Along with implementing the framework for a new application, this study also refines the framework by evaluating multiple impact categories using three impact assessment methods. Findings suggest that with the exception of Fossil Fuel depletion from ReCiPe [25, 26], all impact categories evaluated in Ref. [18] can also be assessed using FEDEFL Inventory methods [24]. This reduces calculation and data treatment time and simplifies the subsequent data gap analysis without significant loss of information.

5.3. LCA Models

In addition to the analysis, an expanded set of LCA models based on those discussed in this study will be published and released on NIST's FLCAC repository for use by NIST and external researchers as well as the LCA community at-large. These include 5 kW, 10 kW, and 20 kWh string inverters, as well as open ground, flat roof, integrated slanted roof, mounted façade, and integrated façade subsystems (see Appendix B).

5.4. Limitations and Future Work

5.4.1. Limitations:

The inventories built in this report might not be representative of current residential photovoltaic system in the U.S. as other inventories developed in Ref. [18] and Ref. [17]. Although they are either contemporary or more recent than commercially available inventories, many of the underlying data is 20 to 30 years old. In addition, unlike inventories in Ref. [17] and Ref. [18], the inventories presented in this report are based on data from Europe. However, in general terms the data gap analysis is considered valid in the U.S. context. For example, data gaps identified are missing on USLCI, and many of them can reasonably be expected to be found in a U.S. residential photovoltaic system— copper in cables, PWB in inverters, etc. However, the relative importance of the gaps might differ from the findings presented here.

5.4.2. Future Work

Based on the limitation above, it would be beneficial to identify and collaborate with U.S. data sources (e.g., Global Electronics Association, Solar Energy Industries Association) to validate current and develop additional inventories more representative of current practices in the U.S.

This report includes many of the inventories identified as next steps in Ref. [18]. However, PV panels not solely based on silicon (i.e., cadmium telluride, CI(G)S and Si-perovskite tandems) are potential future additions. Also, including alternative recycling processes may be of interest to assess new end-of-life scenarios, even if they are not from U.S. based processes. Sections 3.1, 3.2, and 3.3 highlighted the presence of data gaps in the semiconductor and electronics industries, stressing the need to continue research in this sector. Finally, another potential area of expansion of the residential photovoltaic system is the inclusion of batteries, as in Ref. [20].

Outside data gap analysis, the models developed in this report, in Ref. [18], and to a lesser extent in Ref. [17], can be used to develop alternative residential photovoltaic system designs. In combination with data for solar irradiance and regionalized (i.e., balancing authority level) electricity production data, these systems could be evaluated using a full cradle-to-grave analysis through the full life cycle of a PV system [40].

6. References

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Appendix A. List of Symbols, Abbreviations, and Acronyms

ACLCA
American Center for Life Cycle Assessment

AP
Acidification potential

CED
Cumulative energy demand

CED_{NR}
Cumulative energy demand (non-renewable)

CED_{R}
Cumulative energy demand (renewable)

DPGME
Dipropylene glycol monomethyl ether

EI
ecoinvent

EP
Eutrophication potential

EPD
Environmental product declaration

EVA
Ethylene vinyl acetate

FEDEFL
Federal LCA Commons Elemental Flow List

FFP
Fossil fuel potential

FLCAC
Federal LCA Commons

GLO
Global (Ecoinvent geography)

GWP
Global warming potential

HDPE
High density polyethylene

IC
Integrated circuit

IEA
International Energy Agency

ISO

International Standards Organization

LCA
Life Cycle Assessment

LCI
Life Cycle Inventory

LCIA
Life Cycle Impact Assessment

LED
Light Emitting Diode

MSW
Municipal solid waste

NAICS
North America Industry Classification System

ODP
Ozone depletion potential

PCR
Product category rule

PE
Polyethylene

POCP
Photochemical oxidant creation

PV
Photovoltaic

PVF
Polyvinyl fluoride

PVPS
Photovoltaic Power Systems

$[PV]^2$
Present Value of Photovoltaics (NIST tool)

PWB
Printed Wiring Board

RE
Renewable energy (FEDEFL Inventory Indicator)

RER
Rest of Europe (ecoinvent geography)

RFC
Reliability First Council (NERC region)

RNA
Rest of North America (ecoinvent geography)

ROW
Rest of World (ecoinvent geography)

SMD

Surface mounted device

SOP
Surplus ore potential

TH

Through hole

USLCI
U.S. Life Cycle inventory

WATER

Water resources (FEDEFL Inventory Indicator)

WCP
Water consumption potential

Appendix B. Supplemental Material

B.1. Workbooks

The following workbooks were built for and used during the data gap analyses presented here and were made available at https://doi.org/10.6028/NIST.TN.2355sup1

A template was built to quantify data gaps and generate the figures included in the main text. The instructions to use this template are available in Appendix C.

Reduced template: User input, Gap sorting, LCI analysis, Mass, Table, Figures, GWP#4, AP#4, EP#4, ODP#4, POCP#4, NON-RE#4, RE#4, MIN#4, WATER#4, GWP#5, AP#5, EP#5, ODP#5, POCP#5, NON-RE#5, RE#5, MIN#5, WATER#5, GWP#6, AP#6, EP#6, ODP#6, POCP#6, NON-RE#6, RE#6, MIN#6, WATER#6, Calc GWP, Fig GWP, Calc AP, Fig AP, Calc EP, Fig EP, Calc ODP, Fig ODP, Cal POCP, Fig POCP, Calc NON-Re, Fig NON-RE, CALC RE, Fig RE, Calc MIN, Fig MIN, Calc WATER, Fig WATER.

'User input' includes lists of exchanges for the user to label in column I:I, ideally using a short name. Other important user inputs include the cutoff criteria above which exchanges will appear in the figures (set at 1% as default in C2), the unit to which impacts refer to (e.g., kg of material, kWh of energy delivered, etc.), and the name given to the three models assessed. See Appendix C for further information.

'Gap sorting' organized the data gaps. Column A:A indicates whether an exchange in GWP#6 was identified as a data gap. Column B:B lists those data gaps. Column C:C condenses the list of data gaps, while column D:D shortens the names of the gaps.

'Mass' includes the material inputs of model #5, and allows for the quantification of data gaps based on mass input. See Appendix C for further information.

'LCI analysis' presents for models #4 and #6, both built using Ecoinvent, the name of the exchanges and their amount, to facilitate the comparison between the inventories these two models rely on.

'Table' includes the contribution of all data gaps to each impact category as a percentage of the total. There is a raw version, and one that follows the formatting of the report. Columns A:C are used to specify whether any of the gaps is a material input (the user must specify this in Column C:C). Additional columns right of the formatted table are not used

'Figures' collects all the figures form the figure spreadsheets (see below) in one place for easy reference.

Raw results sheets contain the copied openLCA results for a given impact category (GWP, AP, etc.) for one of the three models developed (#4-6). In the Reduced template workbook, these sheets are blank, for the user to populate with the results of their models.

These sheets are: GWP#4, GWP#5, GWP#6, AP#4, AP#5, AP#6, EP#4, EP#5, EP#6, ODP#4, ODP#5, ODP#6, POCP#4, POCP#5, POCP#6, NON-RE#4, NON-RE#5, NON-RE#6, RE#4, RE#5, RE#6, MIN#4, MIN#5, MIN#6, WATER#4, WATER#5, and WATER#6.

Calculation sheets process for each impact category the results of the three models evaluated. Columns C:E include, for model #4, #5, and #6 respectively, total, direct, and indirect impacts, as well as the impacts of each exchange present in that model. Those values higher than the threshold set in 'User Input'!C2 appear in red. Columns H:J include the name of all the exchanges for model #4, #5, and #6 respectively, again highlighting in red the names of those contributing above the threshold to the total impact in the category under assessment. Columns M:O include only the names of those exchanges contributing more than 1% to the total impact of their respective model. Column Q:Q includes the name of all unique exchanges (i.e., combines into a single list the names found in H:J). Column R:R includes a list of unique exchanges with a contribution higher than the threshold. Column S:S looks for the names in R:R in the list of labels created in 'User Input'!I:I. Columns T:V repeat the results from Columns C:E only for those exchanges appearing in Columns R:S. Finally, columns Y:AA add, to the results in T:V, the total, direct, indirect, and calculate the impact of the remaining,"Other" exchanges. The last for columns, X:AA, are used in the Figures spreadsheets (see below).

These sheets are: Calc GWP, Calc AP, Calc EP, Calc ODP, Calc POCP, Calc NON-RE, CALC RE, Calc MIN, and Calc WATER.

Figure spreadsheets include a figure with the impact of the three models for the impact category in their name. The data and labels for the figure is in columns B:F. Columns I:Q include comparison of one set of results against each other. Columns T:V include fraction of total impact attributable to each exchange.

These sheets are: Fig GWP, Fig AP, Fig EP, Fig ODP, Fig POCP, Fig NON-RE, Fig RE, Fig MIN, Fig WATER

Based on this template, the following eight workbooks were created.

1. **Inverter**
2. **Microinverter**
3. **Optimizer**
4. **Electric installation**
5. **Slanted Roof**
6. **System**
7. **Recycling**
8. **Electricity production**

The following workbook was used to develop Table 19 and the analysis in Section 4.2.

Production Chain: Data gaps, Panel, Inverter, Mounting Sys., Elec. In., Recycling

B.2. openLCA models

In addition, the following models based on the representative inventories and built using USLCI datasets (#5 models) will be available in the NIST repository on the FLCAC at [41] and at MIDAS on [42]. They are organized following the North America Industry Classification System (NAICS) codes as follows:

22: Manufacturing

2211: Electric Power Generation, Transmission and Distribution

- Electricity; from 10 kWp slanted-roof multi-Si PV panel; at user

23: Construction

2382: Building Equipment Contractors

- Multi-Si panel; slanted-roof installation; on roof, 10 kWp
- Single-Si panel; slanted-roof installation; on roof, 10 kWp
- Photovoltaic plant; electric installation; at plant; 3 kWp
- Slanted roof construction; mounted; on roof
- Slanted roof construction; integrate; on roof
- Flat roof construction; on roof
- Open ground construction; on ground
- Façade construction; mounted; at building
- Façade construction, integrated; at building

31-33: Manufacturing

3345: Navigational, Measuring, Electromedical, and Control Instruments Manufacturing

- Electronics for control units; at plant

3353: Other Electric Equipment and Component Manufacturing

- Inverter; at plant; 2.5 kW
- Inverter; at plant; 5 kW
- Inverter; at plant; 10 kW
- Inverter; at plant; 20 kW
- Inverter; at plant; 500 W

56: Administrative and Support and Waste Management and Remediation Services

5622: Waste Treatment and Disposal

- Waste c-Si PV panel, takeback and recycling; at treatment plant

Bridge processes

Building Systems to Construction Materials

- Gravel Bridge; Building Systems to Construction Materials
- Ready-mix concrete; 3000 psi Bridge Building Systems to Construction Materials

Building processes to U.S. Electricity Baseline

- Electricity Bridge; Building Systems to U.S. Electricity Baseline

Building Systems to USLCI

- AlMg3 aluminum alloy Bridge; Building Systems to USLCI
- Injection molding Bridge; Building systems to USLCI

- Light fuel oil; combusted in industrial equipment Bridge; Building Systems to USLCI
- Low-alloyed steel Bridge; Building Systems to USLCI
- Packaging film Bridge; Building Systems to USLCI
- Reinforcing steel Bridge; Building Systems to USLCI
- Transport, combination truck, short-haul, diesel powered Bridge; Building Systems to USLCI

Appendix C. Input data gap quantification Excel Templates

Note1: Data gap identification takes place in openLCA while building the representative model in USLCI. These instructions assume the practitioner already knows the production of which flows constitute data gaps.

Note 2: The Excel Workbooks are large files, and lack of memory errors may occur. To prevent this, set “Calculation options” to “Manual”, in the “Formula Tab” while inputting data, and press F9 “Calculate Now” once the data input is complete. The instructions below indicate at the points where it is recommended to “Calculate sheet” (Shift+F9) to ensure the workbook is working properly. It might be necessary to reduce the number of in calculation threads in Options-> Advanced-> Formulas. Two threads should work, although it slows down the calculations.

C.1. Introduction

To facilitate the quantification of the potential impact missing data gaps may generate, the Reduced Template workbook—see Appendix B—is used, and it is referred to heretofore as [Template]

C.2. Mass input contribution

C.2.1. In Excel, enter the cutoff criteria used for both mass inputs, and environmental impacts in [Template]‘User input’!C2.

C.2.2. In Excel, introduce the name of models as you would like them to appear in the figures in [Template]‘User input’!F2:F4.

C.2.3. In openLCA, open the model built using FLCAC processes.

C.2.4. In openLCA, copy the Input from the “Input/output” tab.

C.2.5. In Excel, paste it in [Template]‘Mass’!A1 Data gaps should automatically appear in red and in italics.

C.2.6. In Excel, recalculate [Template]‘Mass’(Shift+F9): Mass data gaps and their contribution should appear in ‘Mass’!P:Q.

C.2.7. In Excel, copy the values from [Template]‘Mass’!P:Q into [Template]‘Mass’!S:T and organize them from high to low. Alternatively, in the “Developer” tab, open Macros, select and run “Convert array to column.”

Note 1: Currently, this worksheet only calculates the relative importance of data gaps if they are expressed in kg, as it adds all amounts in [Template]‘Mass’!C:C if their unit in [Template]‘Mass’!D:D are in kg. They will not be calculated if they are in any other unit, metric or from the U.S. Customary System.

Note 2: To prevent counting waste treatment processes as data gaps —which relate to outputs—or processes that modify a material input—e.g., extrusion, sheeting, etc.—manually delete the "kg" in the appropriate cells of [Template]'Mass'!D:D.

C.3. ISO 29130 impact categories

C.3.1. In openLCA, open the model built using Commercial processes.

C.3.2. In openLCA, in the "General information" tab, create a product system.

C.3.3. In openLCA, calculate impacts using "ISO21930-LCIA-US" Impact assessment method.

C.3.4. In openLCA, in the "Contribution tree" tab, select "Greenhouse Gases" and Copy the results

C.3.5. In Excel, paste the results into [Template]'GWP#6'!A1

C.3.6. In Excel, Select [Template]'GWP#6'!A:F of all rows that constitute a data gap, and format them as Italics. This is how we indicate in Excel that the production/treatment processes of these exchanges are data gaps in the public database.

C.3.7. In Excel, in the "Developer" tab, open Macros, select and run "Red Italics". It should turn all rows in italics red for easy identification. It is not a problem if it does not do it, or if the macro is not run, as its purpose is to facilitate the identification of data gaps when glancing at this spreadsheet. This is an optional step.

C.3.8. In Excel, in the "Developer" tab, open Macros, select and run "CopyItalicCellsInRangeOrganized". It should copy all data gaps to [Template]'GWP#6'!H:M. If it does not, please run the Macro until all data gaps identified appear in rows [Template]'GWP#6'!H:M.

C.3.9. In Excel, ensure the formula in [Template]'GWP#6'!N2 is repeated as many times as there are data gaps.

C.3.10. In Excel, recalculate [Template]'GWP#6'(Shift+F9). If the "RedItalics" macro did not produce any results in step 7, it will likely show them now. ''[Template] 'GWP#6'!Q:Q should include now a sum of the total impact of the data gaps both as a percentage and as an absolute value, as well as the total number of flows whose production process is a data gap.

C.3.11. In openLCA, select "Acidification potential" and copy the results.

C.3.12. In Excel, paste the results into'[Template]'AP#6'!A1.

C.3.13. In Excel, ensure the formula in [Template]'AP#6'!G2 is repeated as many times as there were rows pasted in the previous step.

C.3.14. In Excel, ensure the formulas in [Template]'AP#6'!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]'GWP#6'!Q4.

C.3.15. In Excel, recalculate ‘AP#6’(Shift+F9). [Template]‘AP#6’!G:G should return TRUE for all data gaps, whose cells in [Template]‘AP#6’!A:G should be in red italics. [Template]‘AP#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template]‘AP#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.3.16. In openLCA, select “Eutrophication potential” and copy the results.

C.3.17. In Excel, paste the results into [Template]’EP#6’!A1.

C.3.18. In Excel, ensure the formula in [Template]‘EP#6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.3.19. In Excel, ensure the formulas in [Template]‘EP#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]‘GWP#6’!Q4.

C.3.20. In Excel, recalculate [Template]‘EP#6’(Shift+F9). [Template]‘EP#6’!G:G should return TRUE for all data gaps, whose cells in [Template]‘EP#6’!A:G should be in red italics. [Template]‘EP#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template]‘EP#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.3.21. In openLCA, select “Ozone depletion potential” and copy the results.

C.3.22. In Excel, paste the results into [Template]’ODP#6’!A1.

C.3.23. In Excel, ensure the formula in [Template]‘ODP#6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.3.24. In Excel, ensure the formulas in [Template]‘ODP#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template] ‘GWP#6’!Q4.

C.3.25. In Excel, recalculate [Template] ‘ODP#6’(Shift+F9). [Template] ‘ODP#6’!G:G should return TRUE for all data gaps, whose cells in [Template] ‘ODP#6’!A:G should be in red italics. [Template] ‘ODP#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template] ‘ODP#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.3.26. In openLCA, select “Photochemical oxidant creation potential” and copy the results.

C.3.27. In Excel, paste the results into [Template]’POCP#6’!A1.

C.3.28. In Excel, ensure the formula in [Template] ‘POCP#6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.3.29. In Excel, ensure the formulas in [Template]‘POCP#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]‘GWP#6’!Q4.

C.3.30. In Excel, recalculate [Template] ‘POCP#6’(Shift+F9). ‘POCP#6’!G:G should return TRUE for all data gaps, whose cells in ‘POCP#6’!A:G should be in red italics. [Template]

‘POCP#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template]‘POCP#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.4. FEDEFL Inventory Methods

C.4.1. In openLCA, open the model built using Commercial processes. This step may not necessary if C.3.1 has already been done.

C.4.2. In openLCA, in the “General information” tab, create a product system. This step is not necessary if C.3.2 has already been done.

C.4.3. In openLCA, calculate impacts using “FEDEFL Inventory” Impact assessment method.

C.4.4. In openLCA, in the “Contribution tree” tab, select “nonrenewable_energy” and copy the results.

C.4.5. In Excel, paste the results into [Template]’NON-RE#6’!A1.

C.4.6. In Excel, ensure the formula in [Template]’NON-RE #6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.4.7. In Excel, ensure the formulas in [Template]‘NON-RE#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]‘GWP#6’!Q4.

C.4.8. In Excel, recalculate [Template]‘WCP#6’(Shift+F9). [Template]‘NON-RE#6’!G:G should return TRUE for all data gaps, whose cells in ‘NON-RE#6’!A:G should be in red italics. [Template]‘NON-RE #6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template]‘NON-RE#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.4.9. In openLCA, in the “Contribution tree” tab, select “nonrenewable_energy” and copy the results.

C.4.10. In Excel, paste the results into [Template]’RE#6’!A1.

C.4.11. In Excel, ensure the formula in [Template]‘RE#6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.4.12. In Excel, ensure the formulas in [Template]‘RE#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]‘GWP#6’!Q4.

C.4.13. In Excel, recalculate [Template]‘RE#6’(Shift+F9). [Template]‘RE#6’!G:G should return TRUE for all data gaps, whose cells in ‘RE#6’!A:G should be in red italics. [Template]‘RE#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template]‘RE#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.4.14. In openLCA, in the “Contribution tree” tab, select “USGS_mineral_resources” and copy the results.

C.4.15. In Excel, paste the results into [Template]’MIN#6’!A1.

C.4.16. In Excel, ensure the formula in [Template] ‘MIN#6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.4.17. In Excel, ensure the formulas in [Template]‘MIN#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]‘GWP#6’!Q4.

C.4.18. In Excel, recalculate [Template] ‘MIN#6’(Shift+F9). [Template] ‘MIN#6’!G:G should return TRUE for all data gaps, whose cells in [Template] ‘MIN#6’!A:G should be in red italics. [Template] ‘MIN#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template] ‘MIN#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.4.19. In openLCA, in the “Contribution tree” tab, select “water_resources” and copy the results.

C.4.20. In Excel, paste the results into [Template]’WATER#6’!A1.

C.4.21. In Excel, ensure the formula in [Template] ‘WATER#6’!G2 is repeated as many times as there were rows pasted in the previous step.

C.4.22. In Excel, ensure the formulas in [Template]‘WATER#6’!I2:M2 are repeated as many times as there are data gaps. The number of data gap is the same for all impact categories, and can be found in [Template]‘GWP#6’!Q4.

C.4.23. In Excel, recalculate [Template] ‘WATER#6’(Shift+F9). [Template] ‘WATER#6’!G:G should return TRUE for all data gaps, whose cells in [Template] ‘WATER#6’!A:G should be in red italics. [Template] ‘WATER#6’!I:M should have a list of the data gaps and their contribution to this impact category, and [Template] ‘WATER#6’!P:P should have the total number of impacts, and their contribution to this impact category both in absolute and relative terms.

C.5. Data gap summary

C.6.1. In Excel, recalculate [All Impacts] (F9). As data is being condensed into tables and figures, all worksheets need to be up to date.

C.6.2. In Excel, for each item in [All Impacts]’User input’!H:H, write in their respective cell in [Template]’User input’!I:I the desired short name for those key exchanges (e.g., for “Transport, freight train” in H2 write “Train” I2). Recalculate the worksheet (Shift+F9) to ensure it is updated after your inputs.

C.6.3. In Excel, [Template]’Table’!B:M should have the fraction of the impact caused by each data gap for all impact categories. Columns to the right compare data gaps with one another.

Strictly speaking, this concludes the data gap analysis. However, by adding the results from model #5, also based on Rep., but built with USLCI processes, additional insights into the differences between public and commercial databases can be gained. Adding model #4 offers an additional reference point and can be used to help minimize data input errors (e.g., if the impacts of model #4 and model#6 are significantly different, a typo might have had occurred). To add the results from these two models, a similar procedure to that of model #6 described above should be followed, and it is detailed below for Model#5. The process is identical for model#4.

C.6. ISO 29130 impact categories for additional models

C.7.1. In openLCA, open the model built using public processes.

C.7.2. In openLCA, the “General information” tab, create a product system.

C.7.3. In openLCA, calculate impacts using “ISO21930-LCIA-US” Impact assessment method.

C.7.4. In openLCA, in the “Contribution tree” tab, select “Greenhouse gases” and copy the results.

C.7.5. In Excel, paste the results into [Template]’GWP#5’!A1

C.7.6. In openLCA, in the “Contribution tree” tab, select “Acidification potential” and copy the results.

C.7.7. In Excel, paste the results into [Template]’AP#5’!A1

C.7.8. In openLCA, in the “Contribution tree” tab, select “Eutrophication potential” and copy the results.

C.7.9. In Excel, paste the results into [Template]’EP#5’!A1

C.7.10. In openLCA, in the “Contribution tree” tab, select “Ozone depletion potential” and copy the results.

C.7.11. In Excel, paste the results into [Template]’ODP#5’!A1

C.7.12. In openLCA, in the “Contribution tree” tab, select “Photochemical oxidant creation potential” and copy the results.

C.7.13. In Excel, paste the results into [Template]’POCP#5’!A1

C.7. FEDEFL Inventory Methods for additional models

C.8.1. In openLCA, open the model built using public processes. This step may not necessary if C.7.1 has already been done.

C.8.2. In openLCA, in the “General information” tab, create a product system. This step is not necessary if C.7.2 has already been done.

C.8.3. In openLCA, calculate impacts using “FEDEFL Inventory” Impact assessment method.

C.8.4. In openLCA, in the “Contribution tree” tab, select “nonrenewable_energy” and copy the results.

C.8.5. In Excel, paste the results into [Template]’NON-RE#5’!A1.

C.8.6. In openLCA, in the “Contribution tree” tab, select “renewable_energy” and copy the results.

C.8.7. In Excel, paste the results into [Template]’RE#5’!A1.

C.8.8. In openLCA, in the “Contribution tree” tab, elect “USGS_mineral_resources” and copy the results.

C.8.9. In Excel, paste the results into [Template]’MIN#5’!A1.

C.8.10. In openLCA, in the “Contribution tree” tab, elect “water_resources” and copy the results.

C.8.11. In Excel, paste the results into [Template]’WATER#5’!A1.