NIST Technical Note
NIST TN 2378

Data gap filling in NIST's Building Systems repository with USEEIO bridges

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https://doi.org/10.6028/NIST.TN.2378

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

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July 2026

U.S. Department of Commerce
Howard Lutnick, Secretary

National Institute of Standards and Technology
Arvind Raman, NIST Director and Under Secretary of Commerce for Standards and Technology

NIST TN 2378
July 2026

Publication History
Approved by the NIST Editorial Review Board on 2026-07-09

How to Cite this NIST Technical Series Publication
Rodriguez-Garcia, G. and Kneifel, J. (2026). Data gap filling in NIST's Building Systems repository with USEEIO bridges. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Technical Note (TN) NIST TN 2378. https://doi.org/10.6028/NIST.TN.2378.

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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 in NIST TN 2350 and NIST TN 2355. This last technical note addressed the final application of one semiconductor, a residential photovoltaic system. In this study, those data gaps identified in TN 2350 and TN 2355 that contributed to more than 1 % to an impact category are filled using the United States Extended Environmental Input Output (USEEIO) repository. The scope of this study is to (1) systematize data gap prioritization, (2) fill those data gaps using bridges to the USEEIO repository, and (3) evaluate the effect of filling those gaps has on select impact categories. The study concludes with a series of recommendations to use USEEIO as means of filling data gaps in other repositories.

Keywords

Cell, ISO 21930; FEDEFL inventory indicators, inverter; life cycle assessment; panel; photovoltaic; semiconductors; sustainability.

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Acknowledgments

The authors wish to thank all those who reviewed this manuscript, including Paige Weiler and Ben Morelli at Eastern Research Group Inc. as well as Ms. Sindhu Ranganath, Dr. Behrang Hamadani and Dr. Jason Averill of NIST's Engineering Laboratory (EL).

Author Contributions

Gonzalo Rodriguez-Garcia: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Validation, Visualization, Writing- Original draft preparation.

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 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 to assist U.S. companies in differentiating their products in global markets. 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 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, 19].

This study is designed to complement these three studies by systematizing data gap prioritization and beginning to fill those priority data gaps. As in Ref. [19], the use case is a residential photovoltaic system because it aligns with multiple NIST research programs and addresses the final application of a semiconductor-based technology.

The scope of this study is to:

(1) Establish a systematic approach for the filling of data gaps previously identified.
(2) Filling those data gaps using “bridge” processes to the USEEIO repository.
(3) Evaluate the effect filling those data gaps has on selected impact categories.

Additionally, this study provides recommendations for the use of USEEIO “bridges” to fill data gaps.

2. NIST FLCAC Repositories and Bridge Processes

NIST repositories on the FLCAC include LCA models that use other repositories on the FLCAC for process level data through “bridges” or “bridge processes,”. These are two-exchange processes—one input, one output—connecting two different repositories. In this case, a NIST repository—Building Systems (BSYS) [20, 21]—and either United States Life Cycle Inventory (USLCI) [22] or United States Extended Environmental Input Output (USEEIO) [23, 24]. This approach allows for each repository to be maintained and updated separately while remaining connected to allow for using process data across repositories. To date, LCA models in NIST FLCAC repositories use process data from USLCI for any product or waste not explicitly developed for the NIST repositories. This study introduces bridging models in NIST repositories to the USEEIO repository for process not available in USLCI (i.e., data gaps).

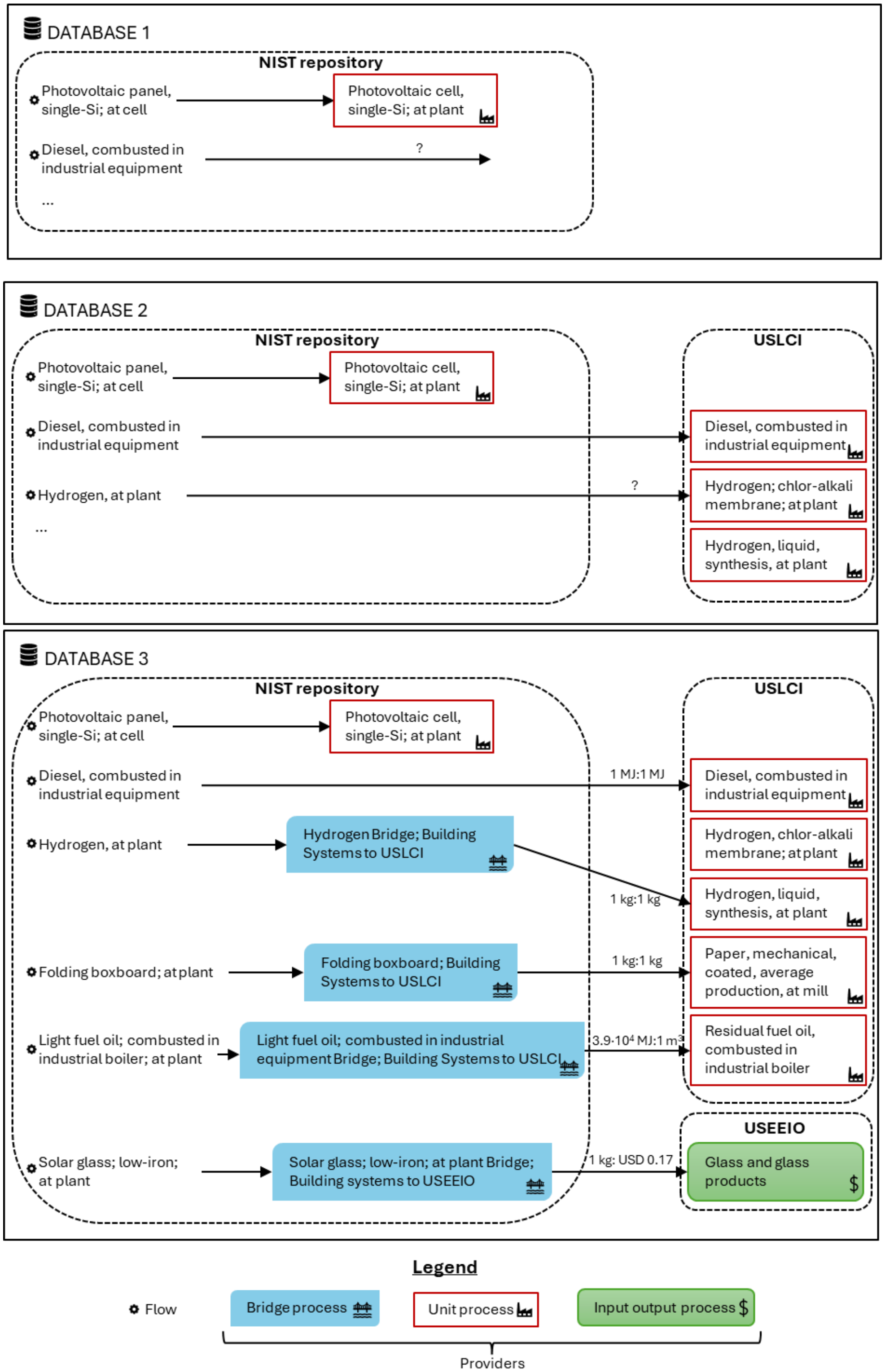
NIST LCA models should be used in an openLCA working space (referred to as a “database” moving forward) that includes both USLCI and USEEIO repositories to allow for the bridging to function correctly. The terminology used in this study varies from that often used in LCA literature, including in previous NIST publications. Thus, it is necessary to define some additional common LCA data-related terms used throughout this study:

Flow: product or material that moves throughout a life cycle, interconnected within the process network. It takes the form of inputs, outputs, energy, or emissions. Flows can be substances, products, materials, energy carriers, emissions, or other types of inputs or outputs (OpenLCA Manual).

- Process: set of interrelated or interacting activities that transform inputs into outputs [6].
- Provider: A reference to a process [...] that provides the product or a waste (treatment) [25]. This term is specific to openLCA, and other LCA software does not use it.
- Dataset: A document or file with life cycle information of a specified product [...] covering [...] quantitative life cycle inventory and/or life cycle impact assessment data [...] [26].
- Database: Container that organizes and stores interconnected elements needed by openLCA. It [contains] projects, product systems, processes, flows, results, and other important components required for conducting LCAs [27]. This definition is specific to openLCA. An openLCA database can contain local copies of multiple repositories (see definition below).
- Repository: A remote or local container in which data are stored under version control, from which a release of contained data can be published [28]. This definition is specific to FLCAC. Elsewhere, collections of datasets are often referred to databases (e.g., the ecoinvent database).

Datasets/repositories can be integrated into a database in openLCA to allow for seamless use of processes for LCA modeling.

Figure 1 represents the different relationships between NIST LCA models and FLCAC repositories. If a NIST repository is the only dataset/repository in a database, only those flows whose production or treatment has been modeled as part of the repository will have a provider (see Database 1 in Figure 1). If a NIST repository and USLCI are in the same database, using USLCI processes when feasible ensures that processes are automatically connected to its available USLCI provider when a product system containing a NIST process is created and its impact calculated. This happens even if the NIST process does not have any provider specified (see Database 2 in Figure 1), because there is often only one provider in the database (i.e., a USLCI process) that becomes its default provider.



Note: Database 1 includes only a NIST repository, Database 2 includes both a NIST repository without bridges and USLCI, and Database 3 includes a NIST repository with bridges as well as USLCI and USEEIO

Figure 1 Repository bridging

Bridges are used to make an explicit connection between two repositories. There are at least three reasons why this may be necessary. First, indicate to the user a provider must be selected among those available in USLCI, since the automatic provider linking in openLCA is inconsistent. This is done by specifying the selected provider in the general description of the bridge process. For example, USLCI contains several routes for the synthesis of hydrogen production. In one instance, when no provider was specified, openLCA selected “Hydrogen, chlor-alkali average, membrane cell; at plant” when calculating a model requiring hydrogen (see Database 2 in Figure 1). If that were not to be the intended source of hydrogen, creating a bridge process, “Hydrogen Bridge; Building Systems to USLCI”, would facilitate linking flows in the NIST repository with the appropriate provider in USLCI (e.g., “Hydrogen, liquid synthesis, at plant”). In addition, bridges allow repositories to only be linked once instead of for every instance where a hydrogen flow appears (see Database 3 in Figure 1).

The second reason for bridges is to indicate that a USLCI provider is a proxy for a process not currently available in USLCI, which is the case of the “Folding boxboard; Building Systems to USLCI” in BSYS. The output is a cutoff flow created explicitly for BSYS, “Folding boxboard; at plant,” which is what was specified in the source report. Although there were no folding boxes in USLCI at the time the BSYS repository was developed, “Paper, mechanical, coated, average production, at mill” was considered sufficiently close to be used as proxy. The benefit of using a bridge process instead of the original USLCI flow and process is that if a more appropriate process were to be made available—in USLCI or elsewhere—the provider could be changed once for all instances of “Folding boxboard; at plant” as opposed to having to replace each individually. These bridges do not require additional input from the user because their purpose is to clearly define the connection between the two repositories.

The third reason why bridges may be needed is for linking two flows between which unit conversion is required. For example, “Light fuel oil; combusted in industrial equipment Bridge; Building Systems to USLCI” links “Light fuel oil; combusted in industrial boiler; at plant,” which is a cutoff flow in BSYS and USLCI’s “Residual fuel oil, combusted in industrial boiler”. These are two different fossil fuels, and although the latter is used as a proxy for the former, this is not done on a 1:1 basis. Instead, based on their energy content, $3.9 \cdot 10^4$ MJ can be obtained from 1 m^3 of residual fuel oil. Bridges to USEEIO, which are the focus of this study, are also an example of this case. They act as a proxy for a process that is not currently available in the NIST repositories or USLCI, and they require a conversion between the physical unit used in those repositories and the price used for the USEEIO equivalent. Thus, price selection plays a critical role in the potential impacts generated by bridge processes to USEEIO.

3. Data prioritization

While developing the BSYS repository [20], 129 non-unique data gaps were identified [18]. Of these, 45 were considered priority data gaps because they were either responsible for at least 1 % of the impact in one category or were more than 1 % of the material input by mass. Between the initial discussion of BSYS in NIST TN 2350 [18] and NIST TN 2355 [19] and the public release of the first version of BSYS on the FLCAC [20, 21], a limited number of these data gaps were filled by using the bridge processes to datasets in USEEIO [23, 24] available in version 1-2025.07.0 of the USLCI repository (USLCI Q2) [22]. This gap filling was limited to selecting those processes considered appropriate (12 in total) and were copied into BSYS. To use some of the models included in BSYS in developing data for the Present Value of PhotoVoltaics—[PV]^2—web application [29], a more systematic approach was developed and is presented here for data gap prioritization and filling.

The long-term goal for NIST repositories in the FLCAC is for data gaps to be filled with unit processes. These are the smallest elements for which inputs and outputs are quantified, and which are linked to other unit processes through intermediary flows, and to the environment through elementary flows [30]. The medium-term goal is to have no data gaps. The gaps will be filled with either system processes, which only link to the environment and not to other human activities, or input-output (IO) data, which are based on monetary flows instead of physical flows. Finally, the short-term goal, addressed here, is for priority data gaps to be filled with any public dataset available.

This short-term goal can be further subdivided into smaller goals for the current final product in BSYS, a residential photovoltaic system. First, fill priority at the residential system level, which are listed in Table 1. For a given impact category, priority data gaps are those contributing more than 1 % to the impact in that category [18, 19]. Thus, the data gaps in Table 1 are those contributing more than 1 % to the Global Warming Potential (GWP) of the whole residential photovoltaic system. Second, fill priority data gaps at the panel level as listed in Table 2. Third, fill priority gaps for each stage or component (e.g., cell production, inverter).

Table 1 Data gaps contributing more than 1 % to the GWP of a 10 kWP PV system.

	% contribution to GWP	Notes
Logic integrated circuit (IC)	19.7	
Solar glass	3.8	
Copper	3.2	Bridge process already included in BSYS 1-2025.06.0
Ring core choke inductor	2.6	
Ethylenevinyl acetate (EVA)	1.5	
Waste plastic	4.3	
TOTAL	**32.0**	

Note: Adapted from Ref. [19]

Table 2 Data gaps contributing more than 1 % to the GWP of Single Si PV panel production

	% Contribution	Notes
Solar glass	7.83	Already listed in Table 1
Wastewater	5.74	Data gap filled in USLCI V1-2025.03.0
Tap water	3.12	Data gap filled in USLCI V1-2025.06.0
EVA	3.01	Already listed in Table 1
PVF film	1.67	Bridge process already included in BSYS 1-2025.06.0
DPGME	1.53	
Glass tempering	1.27	
Factory	1.21	
Argon	1.20	Bridge process already included in BSYS 1-2025.06.0
Metallization paste, front	1.04	
TOTAL	**27.62**	

Note: Adapted from [18], EVA: Ethylenevinyl acetate, PVF: Polyvinyl fluoride, DPGME: Dipropylene glycol monomethyl ether

In total, 41 data gaps were filled using USEEIO across all stages of the production chain for residential photovoltaics. These include those data gaps in Table 1 and Table 2 as well as those identified as a priority for the different stages of the production chain of both residential PV systems and PV panels, Table 3. Data gaps identified in Ref. [18] and Ref. [19] that have already been filled by recent USLCI updates were excluded, including two gaps USLCI had filled through process models (water and wastewater) as well three bridges to USEEIO (argon, copper, and PVF film). In addition to previous data gaps, a 42nd bridge process was modeled for "Liquid crystal display (LCD) module." This is a process used to represent a solar monitoring system, which was not included in the initial BSYS release. It was modeled as a bridge to USEEIO instead of detailed process modeling because it was to have less than a 1 % impact of the whole residential PV system.

Table 3 Data gaps filled using bridge processes to USEEIO

		Stages where it is a priority data gap for at least one category
1	Logic Integrated circuit	Inverters
2	Solar glass; low-iron	Panel
3	Ring core choke inductor	Inverters
4	Ethylene-vinyl acetate	Panel
5	Disposal, hazardous waste, to incineration	
6	Electrolytic capacitor, >2cm height	Inverters
7	Electrolytic capacitor, <2cm height	Inverter (not a priority)
8	Film capacitor; through-hole mounted	Inverters
9	Printed wiring board	Inverters, string optimizer
10	Surface mounded (SMD) glass diode	Microinverter
11	Low voltage transformer	Microinverter
12	Disposal, non-hazardous waste, to incineration	
13	Tantalum capacitor; through-hole mounting	Microinverter

		Stages where it is a priority data gap for at least one category
14	Clamp connector	Microinverter
15	Network cable without plugs	String optimizer
16	Ribbon cable	String optimizer
17	Disposal, plastic waste, unspecified[1]	Recycling
18	Disposal, plastic waste, unspecified[1]	Recycling
19	Metal working factory	String inverter (not a priority)
20	Wafer factory	Wafer
21	Silicon factory	Metallurgical and solar grade Si
22	Photovoltaic cell factory	Cell
23	Photovoltaic panel factory	Panel
24	Metallization paste; front side	Cell
25	Metallization paste; back side	Cell
26	Metallization paste; back side, aluminum	Cell
27	Silicone product, at plant	Panel
28	Pallet, for packaging	Panel
29	Dipropylene glycol monomethyl ether	Wafer
30	Tempering, flat glass	Panel
31	Steel section bar rolling	Inverters, Mounting system
32	Copper wire drawing	Electric installation
33	Nitrogen	Single Si, cell
34	Isopropanol	Single Si, panel
35	Silane	Single Si
36	Phosphoryl chloride	Single Si
37	Brass	Wafer
38	Linear alkylbenzene sulfonate	Wafer
39	Water, process, deionized	Wafer
40	Nitric acid, at plant	Single Si
41	Charcoal	Metallurgical grade Si
42	LCD module	Residential System

Note: 1. These flows refer to two different end-of-life treatments for plastic waste: combustion and landfilling. Two bridges were created for them (see USEEIO Bridges Excel file in Appendix B). and used for the analysis in the following sections. However, they are not available as part of the update BSYS repository. This is because USLCI 1-2025.12.0 included unit processes for the landfilling and combustion of plastics. Thus, the USLCIA flows "Mixed plastics, landfilled" and "Mixed plastics, combusted" were added to the BSYS repository, so they can be linked with the appropriate USLCI providers.

As indicated at the end of Section 2, the price selected for each of these gaps will be one of the main drivers of the potential impacts caused by their bridge processes. Thus, prices selected are presented on Table 4. Note that in addition to other factors explained in Section 4, unit conversions and other calculations were used to make the data in the original sources suitable for the bridge process. These calculations can be seen in the [USEEIO bridges] workbook, available through a link in Appendix B.

Table 4 Prices used for the USEEIO bridges

	Price	Price per	Source	Notes
Logic Integrated circuit	$2.91	unit	[31]	Ordering 2450 units
Solar glass; low-iron	$2.63	m^2	[32]	3.2 mm double layer coating
Ring core choke inductor	$6.71	unit	[33]	Ordering 96 units
Ethylene-vinyl acetate	$1,362.16	Mg	[32]	
Disposal, hazardous waste, to incineration	$60.05	ton	[34]	
Electrolytic capacitor, >2cm height	$10.47	unit	[35]	
Electrolytic capacitor, <2cm height	$0.15	unit	[36]	Ordering 25,000 units
Film capacitor; through-hole mounted	$1.20	unit	[37]	Ordering 10,000 units
Printed wiring board	$0.67	unit	[38]	0.1*0.1 m2, thickness 1.2 mm
Surface mounded (SMD) glass diode	$0.02	unit	[39]	Ordering 5000 units
Low voltage transformer	$7.86	unit	[40]	
Disposal, non-hazardous waste, to incineration	$50.00	ton	[41]	
Tantalum capacitor; through-hole mounting	$1.14	unit	[42]	Ordering 10,000 units
Clamp connector	$0.22	unit	[43]	
Network cable without plugs	$189.00	1000 ft	[44]	
Ribbon cable	$7.39	5 units	[45]	
Disposal, plastic waste, unspecified	$56.80	ton	[46]	
Disposal, plastic waste, unspecified	$50.00	ton	[41]	
Metal working factory	$130.80	m^3	-	USLCI bridge process
Wafer factory	$130.80	m^3	-	USLCI bridge process
Silicon factory	$130.80	m^3	-	USLCI bridge process
Photovoltaic cell factory	$130.80	m^3	-	USLCI bridge process
Photovoltaic panel factory	$130.80	m^3	-	USLCI bridge process
Metallization paste; front side	$1,235.60	kg	[32]	Average busbar and finger
Metallization paste; back side	$822.87	kg	[32]	
Metallization paste; back side, aluminum	$10.00	kg	[47]	Lowest price
Silicone product, at plant	$9,463.00	tonne	[48]	
Pallet, for packaging	$8.41	unit	[49]	
Dipropylene glycol monomethyl ether	$2,002.00	tonne	[50]	
Tempering, flat glass	$0.79	m^2	[51]	30% more than regular glass
Steel section bar rolling	$0.55	kg	[52, 53]	Difference NUCOR Consumer and Chicago scrap
Copper wire drawing	$13.84	Kg	[54, 55]	Difference between wire and copper
Nitrogen	$0.47	m^3	[56]	Average for mid volume users
Isopropanol	$1,362.00	Mg	[57]	Q2 2025
Silane	$2.50	kg	[58]	Average between $2-3
Phosphoryl chloride	$209.52	kg	[59]	
Brass	$1.66	lb	[60]	Average 12 months 09/24/25
Linear alkylbenzene sulfonate	$700.00	Ton	[61]	90 % purity, sulfonic acid

	Price	Price per	Source	Notes
Water, process, deionized	$0.65	m^3	[62]	Contract price 09/2020
Nitric acid, at plant	$1,362.00	Mg	[63]	Prices for Q2 2025
Charcoal	$599.97	Pallet	[64]	33 lb*28 bags pallet
LCD module	$20.92	Unit	[65]	

4. Resources and procedure

Instructions on how to create bridge processes to USEEIO are available in the FLCAC Github repository [66]. Although not publicly available, an Excel Workbook was developed by Eastern Research Group (ERG) to facilitate the development of conversion factors to US dollars (USD), and generate the description of the bridge process [67]. The content of the worksheet is detailed in Table 5.

Table 5 Original USEEIO v2 Conversion Worksheet

	Description
SourceFlowName	Name of the flow to be linked to USEEIO. Often a CUTOFF flow from USLCI
SourceUnit	Unit in which the source flow is measured (kg, unit, etc.)
TargetFlowName	Name of the USEEIO flow
TargetFlowUUID	Universal Unique Identifier number of the target flow
TargetFlowContext	Folder where the target flow is found (Technosphere flows/XX: NAICS Sector/XXXX NAICS sector)
TargetUnit	Unit in which the target flow is measured. By default, USD.
PPI Conversion	Producer price index. This is calculated following the instructions in [66] as $Cost\ Conversion * \frac{\mathrm{X}Rho}{2012\ Rho} * 2012\ \mathrm{Phi}$ Where 20XX Rho is the consumer price index for the year X, which currently must be 2023 or earlier. 2012 Rho is the consumer price index for the year 2012, which is currently the model year for USEEIO V2.
Cost Conversion	Conversion of the value in “Cost” to match the units in “SourceUnit” Formulas vary on a case-by-case basis.
Cost	Cost of the product/service in USD per the amount specified in “Cost Unit”
Cost Unit (price per …)	Unit on which the “Cost” is based
Cost year	Year for which “Cost” is valid
Cost source	Link to the source of the cost
Cost Conversion	Additional conversions that might be required to obtain a “Cost” per “SourceUnit”
Note	Units for “Cost Conversion”
NAICS	North American Industry Classification System numbers. They are often of the form XXXXXX/U.S.
2023 Rho	Rho, price adjustment factor for a given commodity, for the year 2023 (Most recent year for which values are available) [24]
2012 Rho	Rho for the year 2012 (Reference)
2012 Phi	Phi, ratio of producer price over purchaser price for a given commodity, for the year 2012 (Reference) [24]
(Unnamed column)	Combines information from several other columns to concatenate a text that serves as a description of the bridge process

ERG’s original work was expanded and, whenever possible, automated here to facilitate the addition of bridge processes to the worksheet, and to generate worksheets that are exportable into openLCA. Table 6 describes the changes made to the worksheet. All those columns not included remain as in the original worksheet.

Table 6 Modified USEEIO v2 Conversion Worksheet

	Description
(Unnamed column)	The code for the bridge process is used as reference to develop worksheets that can then be exported to openLCA. It is the number of the row -1.
SourceFlowRepository	Repository where the SourceFlow is found. This is used to classify the resulting bridge process
TargetFlowName	Names are now available from a dropdown menu based on all the USEEIO processes, included in 'USEEIO_process_list'
TargetFlowUUID	The UUID of the target flow is returned based on "TargetFlowName"
TargetFlowProxy	TRUE/FALSE If left empty, it is read as FALSE
TargetFlowContext	Auto populated based on "TargetFlowName" and the data on 'USEEIO_process_list'
NAICS	Auto populated based on "TargetFlowName" and the data on 'USEEIO_process_list'
2023 Rho	Auto populated based on "TargetFlowName", "Cost year", and the values on 'Rho'. If more recent than 2023, 2023 is used
2012 Rho	Auto populated based on "TargetFlowName" and the values on 'Rho'
2012 Phi	Auto populated based on "TargetFlowName", and the values on 'Phi'
(Unnamed column)	Regularized to include all information without the use of helper columns

To better follow this Subsection, please open the [USEEIO bridges] workbook, add the "Bridge addition USEEIO" and "ResultsRunner" code to your development environment, and open the database of choice in openLCA.

A two-exchange 'Template' sheet was built with the USEEIO exchange as input, and the non-USEEIO exchange as output. As in workbooks developed previously [RegionalizationReport], a macro (GenerateSheetsFromTemplate_ByColumnB) copies the 'Template' worksheet, renames the sheet using the code numbers on 'USEEIO_process_list'!B:B. Based on that code, the renamed template is populated with the appropriate data for each bridge process. In addition, the columns "Name", "Category", and "description" in 'General information' are also populated based on the information collected in 'USEEIO_process_list'.

Once all desired bridge processes have their own worksheet and 'General information' is populated to include those same processes, the Python Code "Bridge addition USEEIO" should be used to add them to openLCA. This is a modified version of the "Bridge process addition" introduced in Ref. [RegionalizationReport] that serves the same purpose, the export of LCA models built in Excel into the dedicated software openLCA [68]

To facilitate data extraction for comparison in Excel, a Python tool (ResultsRunner) was developed [RegionalizationReport]. In an Excel workbook, the user introduces the names of the processes to be assessed and the impact assessment methodologies to be applied. After running the code, an Excel workbook is created with the LCI, overall impacts, and first level contributions to those impacts. The latter is optional, and can be ignored by changing line 46 to:

PERFORM_CONTRIBUTION_ANALYSIS = False

This speeds up the calculation process significantly because it is necessary to calculate the impacts of each exchange individually to ensure the results from the contribution analysis match those given by openLCA—see Section 5.1.

5. Results and discussion

One of the benefits of ResultsRunner is the capability of running multiple impact assessment methods for the same models. However, only the results related to the impact categories from ISO 29130 [14] are presented here for simplification: GWP, eutrophication potential (EP), acidification potential (AP), photochemical oxidant creation potential (POCP), and ozone depletion potential (ODP). Impacts for the other method used in Ref. [19], Federal LCA Commons Environmental Flow List (FEDEFL) Inventory Methods[69], are included in Section 5.3.5.

5.1. ResultsRunner validation

To test ResultsRunner, the original results for the residential photovoltaic system and its components presented in Ref. [19] were compared with those obtained with ResultsRunner. For reference purposes, the notation for the models from NIST TN 2338 is presented here Table 7. Comparisons are focused on models using a “representative” inventory built with either a commercial (#6) or public (#5) repository and are referred to as “Commercial-Original” or “Public-Original” models heretofore.

Table 7 Round robin model numbering

Model	Inventory	Repository
#1	Public	Public
#2	Public	Commercial
#3	Commercial	Public
#4	Commercial	Commercial
#5	Representative	Public
#6	Representative	Commercial
#7	Representative	Representative

Adapted from [17]

First, models built with commercial (i.e., ecoinvent) datasets were tested. Results of the original models are called “Commercial-Original” while those from ResultsRunner are simply called “Commercial”. Relative differences—Equation 1—between the results of the models are negligible (less than 10e-13), validating the results from ResultsRunner.

$$\frac{Impac_{Commercial,Recalculated} - Impact_{Commercial}}{Impact_{Commercial}} \cdot 100 \qquad \textbf{Equation 1}$$

A similar comparison of the models built using USLCI datasets, “Public-Original” and “Public” is shown in Table 8. Results did not show the same level of agreement as for the commercial models. There are significant differences, especially regarding the electric installation and truck transport.

Table 8 Relative difference between the impacts of “Public-Original” and “Public” models for the residential photovoltaic system and its components

	GWP	EP	AP	POCP	ODP
System	-3 %	0%	-2%	-2%	-3%

	GWP	EP	AP	POCP	ODP
Single Si panel	-3 %	0%	-3%	-3%	-3%
String inverter	-3 %	-2 %	-2 %	-1 %	-4 %
Slanted roof	0 %	-4 %	0 %	0 %	-12 %
Electric Installation	-12 %	-5 %	-15 %	-10 %	-8 %
Train	-2 %	0 %	-2 %	-1 %	-11 %
Truck	-21 %	-85 %	-21 %	-23 %	-100 %
Electricity	0 %	0 %	0 %	0 %	0%

GWP: Global warming potential, EP: eutrophication potential, AP: acidification potential, POCP: photochemical oxidant creation potential, ODP: ozone depletion potential

It is hypothesized that changes across version releases of USLCI are causing these differences. This hypothesis was tested by rerunning the models built with USLCI directly in openLCA. A high degree of agreement was found for these rerun models and "Public" models, with negligible relative differences (less than 10e-10), further validating ResultsRunner. This is, ResultsRunner was able to replicate the results from openLCA for the models as they currently are in the database. However, the models built with USLCI as they are in the database now have different results than those in the original reports. Because it is not possible to replicate the results from the previous reports, a new baseline model was created—see Section 5.2.

5.2. Overall system comparison

The reference inventories used to create Public models are available on a FLCAC repository, BSYS [21]. This repository is combined with USLCI 1.2025-09.0 [70] and USEEIO V2 [23]. Resulting models are identified as "Public-Updated". These baseline models use only preexisting bridge processes, including the three bridges discussed in Section 3, and additional bridge processes for other exchanges. These 24 additional bridges apply to non-priority data gaps, or to exchanges appearing in stages of the production chain that were not evaluated in Refs. [18, 19], Table 9.

Table 9 Additional USLCI to USEEIO bridges used in the production chain of photovoltaic systems

Agrochemicals, at plant	Hydrogen peroxide
Aluminium sulphate, powder	Iron Sulphate
Brick	Light emitting diode
Building construction, hall, steel construction	Nitrogen
Chemical, unspecified, for wastewater treatment	Polymers
Clay, at mine	Silicone
Concrete	Sodium hydrogen Sulfite, 40 % in solution
Cotton Textile	Sodium hypochlorite, 15% in H2O
Ethoxylated alcohols	Sodium Tripolyphosphate
Excavation, hydraulic digger	Solvent, at plant
Flat glass	Titanium dioxide
Gravel, unspecified	Zeolite

ResultsRunner is used to calculate the impacts for the photovoltaic system, which are normalized to 100%. The Public-Updated model for photovoltaic system is used as reference to compare three other models of the same system: Commercial, Public, and a new model (Public-Bridged). To build this new model, the Public-Updated model was modified using the Python code introduced in Section 4 ("Bridge addition USEEIO") to add all new bridges to USEEIO. The comparison between these three models is shown in Figure 2.

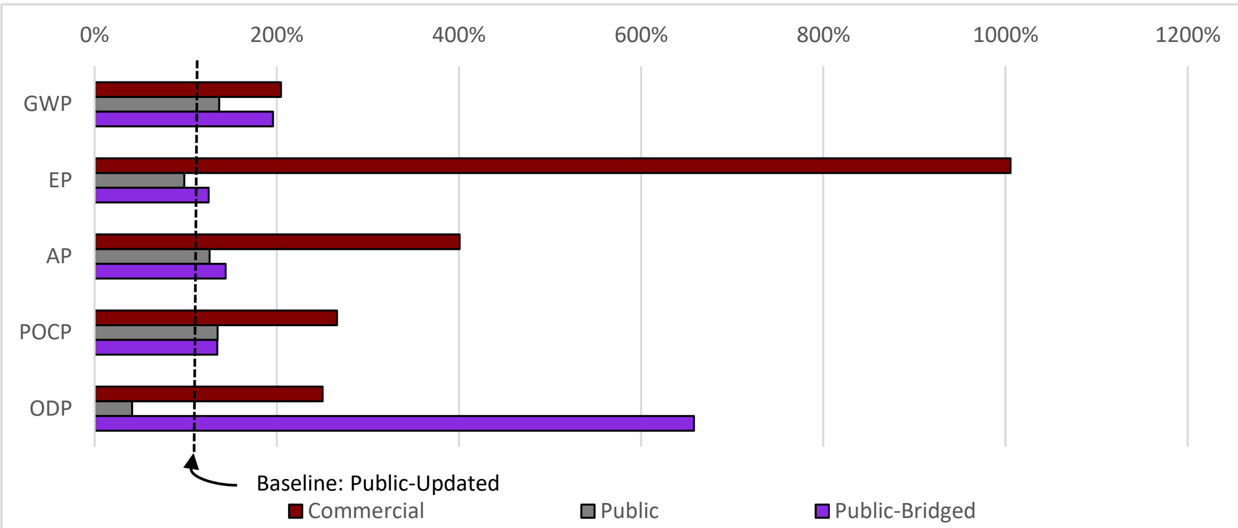


Figure 2 Normalized impact of the different photovoltaic system models.

The Public-Bridged model almost doubles the GWP of the Public model, which is consistent with the results in Ref. [19] showing data gaps accounting for 41 % of the Commercial model.[1] Nevertheless, the GWP of the Public-Bridged model remains 4 % lower than that of Commercial. Relative results for other impact categories vary from GWP. For ODP, the impact of the Public-Bridged model is higher than that of the Commercial model—2.6 times higher. For the remaining three impact categories, the Commercial model generates higher impacts (between 2 and 8 times higher) than the Public-Bridged model. These results point to key differences between repositories for non-GWP categories. The Commercial model resulted in a higher EP than both Public models. Contrarily, Public-Bridged resulted in higher ODP than the Commercial model. The reasons for these differences, and whether they are part of a trend cannot be confirmed by solely evaluating the total impact of the different photovoltaic models. For that reason, a more detailed analysis of the source of these impacts is required.

5.3. Data gap filling analysis

Commercial and Public-Bridged models can be considered "complete" when compared with Public-Updated models because the priority data gaps in Table 3 have been filled. In the case of Commercial models, no gaps existed because it uses the commercial repository. For the Public-Bridged models, priority gaps were filled primarily using bridges to USEEIO processes, as

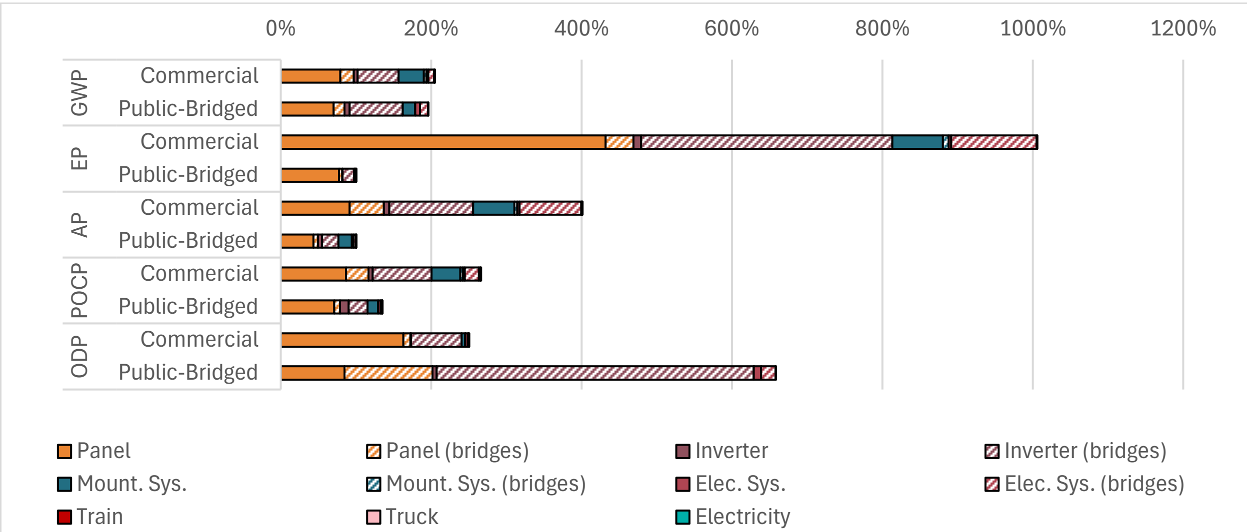
[1] No other impact categories were assessed at that level in Ref. [1], preventing further comparison with previous results.

described in Section 4. The purpose of comparing these two sets of models is to explain the differences observed in Figure 2. Specifically, evaluate whether the causes of those differences can be identified at the photovoltaic system level (Section 5.3.1), or whether they are part of a larger trend through the production chain (inverter in Section 5.3.2, photovoltaic panel in Section 5.3.3, and photovoltaic cells in Section 5.3.4).

5.3.1. Photovoltaic System gap filling analysis

Figure 3 shows the normalized impacts of Commercial and the Public-Bridged models for the photovoltaic system, broken down by their sources. In addition, the results for Public-Bridged model are further divided to indicate the fraction of bridge processes. For the Commercial model in Ref. [19] the panel was the main source of GWP—the only impact category evaluated at this level—and the main data gaps were found in the inverter. For Public-Bridged model, the inverter is the main source of GWP, mostly because of gaps filled with bridge processes. In Ref. [19], identified gaps from the inverter were responsible for 27 % of the GWP while in the Public-Bridged model, the bridges generate 36 % of the impacts. Contrarily, the bridges from the panel are responsible for 7 % in the Public, Bridged model, but identified gaps generated 9 % of the GWP in Ref. [19].

The preponderance of the inverter and its related bridge processes as the main source of impact is only replicated for the Public-Bridged model in ODP. In EP, AP, and POCP, the combined importance of preexisting process and bridge processes —of the inverter, but also of the panel and other components—is noticeably smaller for the Public-Bridged model than for the Commercial model. This supports the hypothesis that bridge USEEIO processes have lower EP and higher ODP than their commercial dataset equivalent unit processes. In addition, it suggests they have a relatively similar GWP and smaller AP and POCP. To confirm these hypotheses, the two main sources of impact from bridge processes: inverter and panel are assessed in more detail in section 5.3.2 and 5.3.3 respectively.

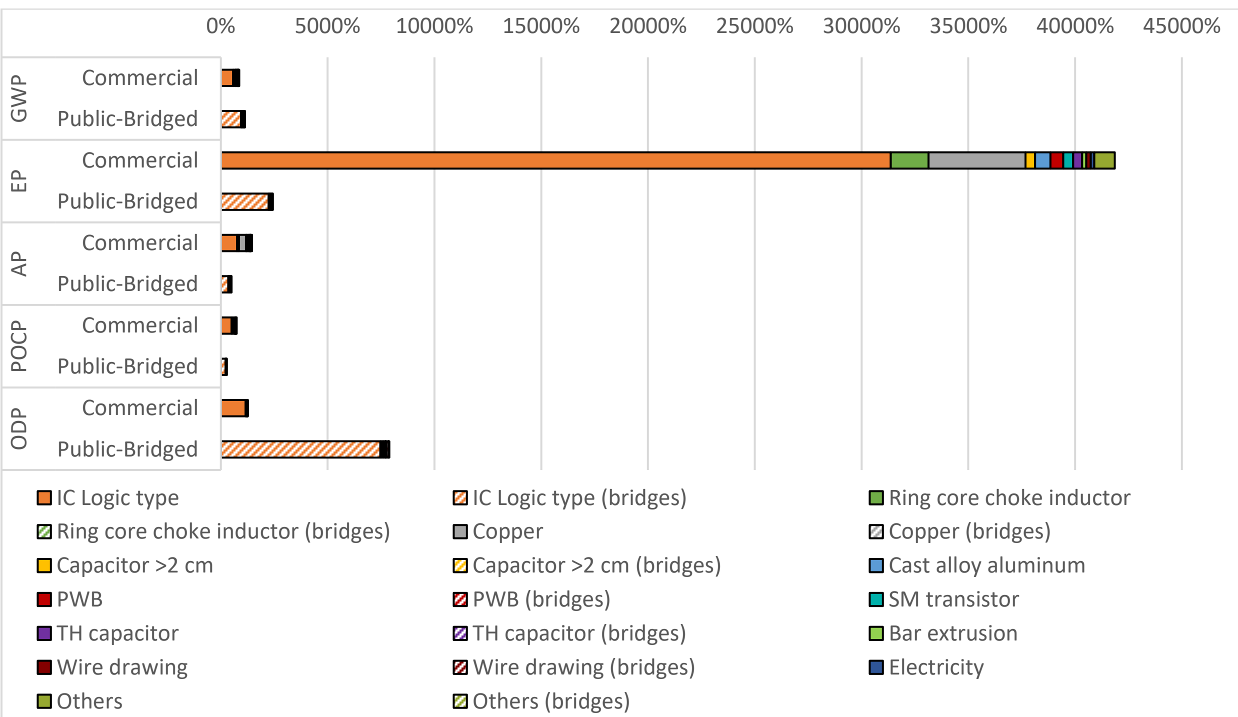


Note: The basis of 100 % is the Public-Updated model for the photovoltaic system.

Figure 3 Impact contribution from the different components of the photovoltaic system

5.3.2. String inverter gap filling analysis

Figure 4 supports the first hypothesis: The lack of processes for the production of electronic components in USLCI (previously discussed in Ref. [19]) makes the baseline small compared to more complete models, hence the high percentage changes. Differences of scale aside, the most noticeable aspect of Figure 4 is that despite having filled 16 data gaps with bridge processes, the contribution of only a handful of them is greater than 1 % for at least one impact category. Across impact categories, the key data gap filled is the logic type integrated circuit (IC), which had been identified as the main contributor to all impact categories evaluated in Ref. [19]. Although the preeminence of the logic type IC was expected based on previous work, the virtual absence of many bridge processes was not expected. Because many of the filled data gaps—including the logic type IC—are linked to USEEIO's "Electronic capacitors, resistors, coils, transformers, connectors and other components (except semiconductors and printed circuit assemblies)," it is possible prices for the logic IC are higher than what they should be when compared to other electronic components. As shown on Table 4, most prices from electronic components come from suppliers such as Mouser, where large quantities of electronic components can be ordered—and therefore reflect economies of scale. However, the range of products that fit into the description of an exchange listed in the representative inventory is such that any selection creates uncertainty. That is, the product selected (and for which prices are given), might not be the most appropriate for that specific electronic component in an inverter used for residential photovoltaics.



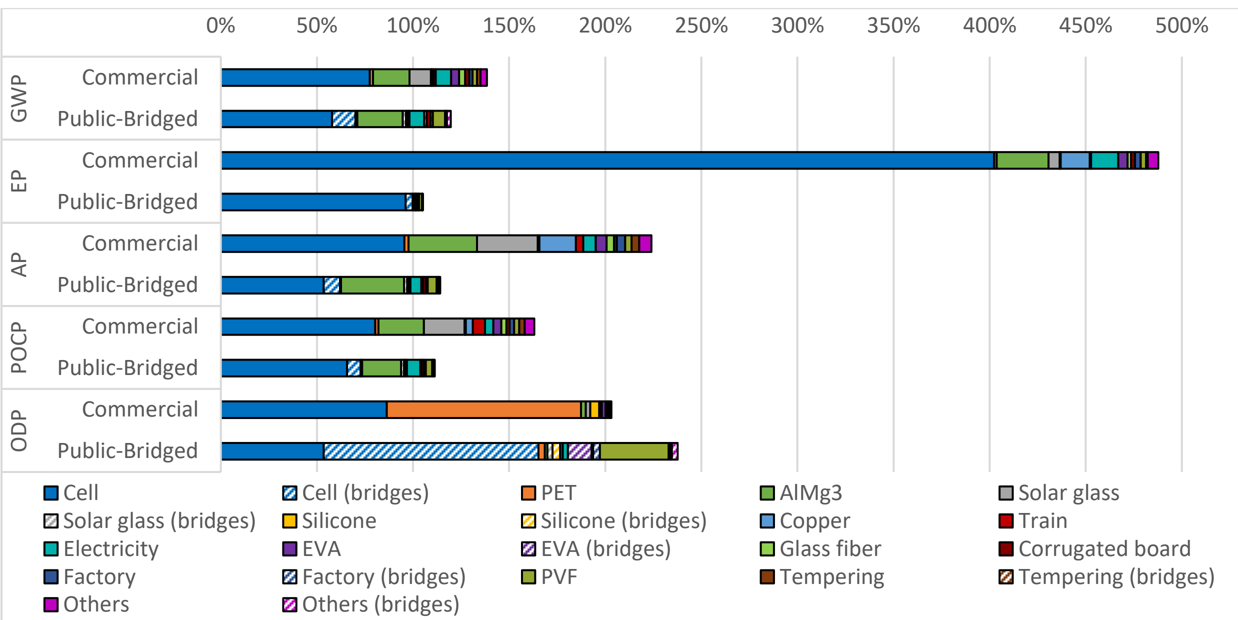
Notes: 1) The basis of 100 % is the Public-Updated model for the inverter. 2) Only processes contributing 1 % to at least one of the impacts are shown individually. The remaining are combined into "Others" and "Others (bridges)".

Figure 4 Impact contribution for production of 2.5 kW string inverter

The results on Figure 4 support only half of the second hypothesis: AP and POCP are lower for USEEIO bridges than unit processes from the commercial repository. The impacts for the Public-Bridged model are 66 % and 56 % lower, respectively, than for the Commercial model. However, with the GWP of the Public Bridged model being 30 % higher than that of the Commercial model, it is harder to consider them similar, as hypothesized based on the 4 % difference shown in Figure 3.

5.3.3. Photovoltaic panel gap filling analysis

Figure 5 shows the normalized impacts of the Commercial and Public-Bridged models by their sources for single-Si photovoltaic panels. Similar to inverter, the contributions of many bridge processes are smaller than 1 %. The clear exception is "Cell (bridges)", which combines all the bridges used in previous steps of the production chain—wafer manufacturing, single silicon production, etc.—in addition to those occurring during cell manufacturing. Bridge processes related to previous steps of the production chain are clearly important, particularly for ODP, and are further assessed in section 5.3.4. Focusing on the gaps from the manufacturing of the solar panel, only one—EVA—and for one impact category—ODP—has a noticeably larger impact than its equivalent in the Commercial model—6.5 times. However, the impacts of the USEEIO bridge for the other impact categories are only 11 % to 32 % of those for the commercial dataset. This indicates that, as previously hypothesized, the USEEIO processes used to model EVA, "Synthetic rubber and artificial and synthetic fibers," has a much larger ODP than its commercial dataset equivalent while having a much lower impact for EP and, to a lesser extent, the other four impact categories evaluated.



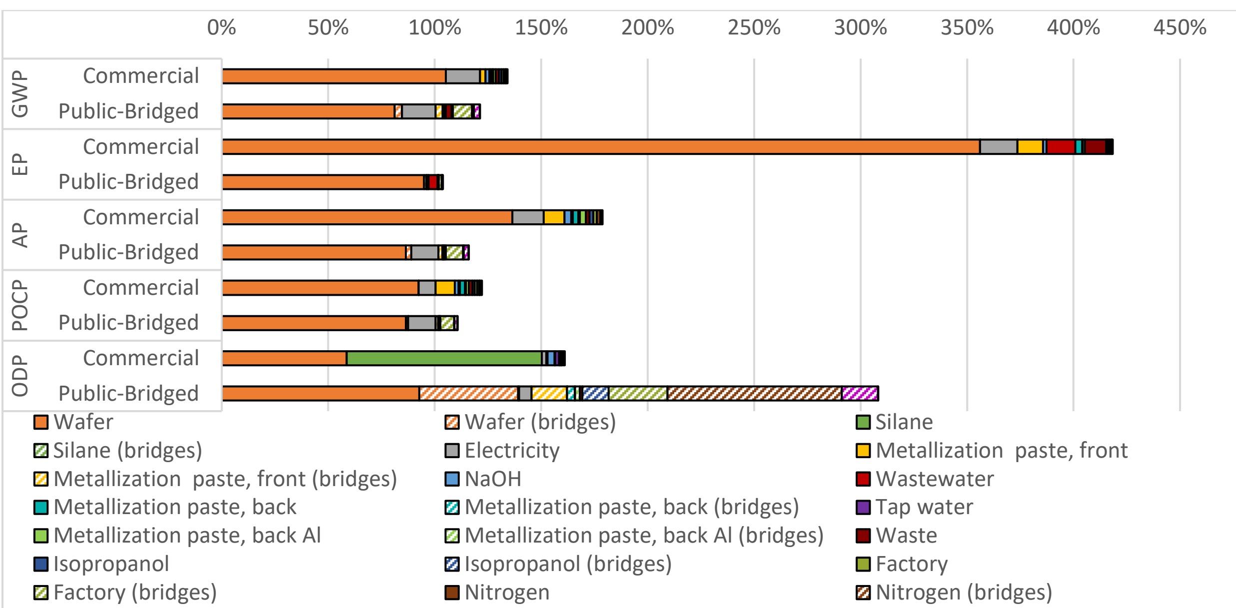
Notes: 1) The basis of 100 % is the Public-Updated model for the photovoltaic panel. 2) Only processes contributing 1 % to at least one of the impacts are shown individually. The remaining are combined into "Others" and "Others (bridges)".

Figure 5 Impact contribution for production of the photovoltaic panel

Solar glass is a significant contributor to most impact categories for the Commercial model. However, despite having filled that gap using USEEIO, the contributions of this glass in the Public-Bridged model are typically much smaller, 4-14 % of the impacts of the Commercial model. The exception is ODP, where it is 112 % higher. After reviewing the USEEIO bridge—unit conversions and prices—a plausible explanation might be that the manufacturing of solar glass is substantially more impactful in most categories than that of regular glass. This is, solar glass may not be as well represented by the USEEIO process "Glass and Glass products" as regular glass is. However, this hypothesis is not supported by the models in the commercial repository, which equate solar glass and uncoated glass.

5.3.4. Photovoltaic cell gap filling analysis

To offer an additional layer of results, cell production is evaluated in detail in Figure 6. As in section 5.3.3, the focus is on the bridges related to cell production (i.e., excluding bridges from wafer production and previous stages), which are small except for ODP. The contributions of bridge processes to ODP are generally higher than that of their commercial dataset counterparts. The largest contributor is N_2, the sole exchange linked to USEEIO's "Compressed Gases". Thus, it may be that impacts of this sector are higher for ODP than the production of N_2 according to the commercial repository. However, the price selected for N_2 also plays a role. An average price for mid volume users of \$0.47/m^3 (0.0018 \$/gal) was selected—Table 4 and Ref. [56]. According to the same source, prices for high volume users—which might not be the case of solar cell producers—could be as low as \$0.12/m^3 (0.0004 \$/gal). This would reduce the impact of N_2 proportionally.



Notes: 1) The basis of 100 % is the Public-Updated model for the photovoltaic cell. 2) Only processes contributing 1 % to at least one of the impacts are shown. The remaining are combined in "Others" and "Others (bridges)".

Figure 6 Impact contribution for production of single Si cells

Phosphoryl chloride is a process linked to USEEIO's "Other basic inorganic chemicals." Its price used in the bridge process is much higher than for other chemicals—\$209.52/kg (\$95.04/lb) versus \$2.5/kg (\$1.13/lb) for silane—Table 4. While $POCl_3$ may be more expensive than silane, it needs to be noted that due to data availability the price for $POCl_3$ is taken from a lab supplier [59], and not from a market industry report as is the case for silane [71]. Therefore, its price is potentially inflated when compared to other chemicals, and thus so are its impacts. This is one of the facets of the sensitivity of USEEIO bridges to prices. Ideally, values used should reflect industrial exchanges, where bulk prices and economies of scale play a role. When retail prices are used, as for phosphoryl chloride in this application, overestimations are likely to occur.

In the opposite direction is the relatively low ODP impact of silane in the Public-Bridged model when compared to that in the Commercial model, where silane is the main contributor. This is because the commercial dataset process used, "dimethyldichlorosilane production" that accounts for the direct emission of $CHCl_3$, a minor chlorofluorocarbon (CFC), which cannot be covered in a high-level input-output model. It should be noted that the correct process in the commercial database for silane production would have been "silicon tetrahydride production, silicon hydrochlorination", which does not directly generate CFCs.

Finally, the solar cell factory is responsible for 9 % of the ODP for the Public-Bridged model, and except for EP, its contribution is similarly important in other categories. The price used—\$138.8/m^3 (\$3.93/m^3)—is taken from the equivalent USLCI bridge process, as shown on Table 4. It is the same price used for the photovoltaic panel factory in Figure 5, where the factory contributes less than 1 % to all impacts evaluated. The conversion from m^3 to units—how price is reported in USEEIO vs how factories are modeled in the inventory—is a straightforward calculation of the area of a cell factory [72] multiplied by height of an average factory [73]. The disparity of results may originate from the difficulty in defining the fraction of factory unit required to produce one functional unit of product. In this case, how much of a photovoltaic cell factory is needed to produce 1 m^2 of cells.

The reference photovoltaic cell factory in the commercial repository is in Gelsenkirchen, Germany that operated between 1999 and 2018 with production reported to be 10 million solar cells per year over its expected lifetime of 25 years [74]. However, Ref. [75], which was the base for the representative inventory of the photovoltaic panel, used ecoinvent to build their models while reporting 4.0E-7 units of photovoltaic cell factory used per m^2 of cells. This is not consistent with the ecoinvent model because it implies cells of 0.01 m^2 (15.50 in^2). For reference purposes, Ref. [75] mentions a 0.0252 m^2 wafer (39.06 in^2), ecoinvent a 0.023104 m^2 (35.81 in^2) cell, and de Wild-Scholten cells of 0.024336 m^2 (37.72 in^2) [76]. The value of 4.0E-7 factories/m^2 (2.58E-10 factories/in^2) can be traced back to an ecoinvent 2.2 report [77]. The source reported there, Ref. [78] uses a factory producing 9 million cells/year for 25 years. Although it might be unclear whether these cells are of 0.024336 m^2 or 0.015625 m^2 (37.72 in^2 and 24.22 in^2 respectively), either is still noticeably smaller than what is reported in Ref. [[75]—1.83e-7 units and 2.84e-7 units (factories), respectively. Therefore, it is possible the reference inventory and current ecoinvent models are overestimating the amount of factory required for production of a cell.

Finding the original source of the plant size/production rate explains the results on Figure 6. This 9 million cells/year plant was 1600 m^2 (17222 ft^2) [78]. The factory used here for the USEEIO bridge, ES Foundry in Greenwood, SC is approximately 23 times that size— 37,161 m^2 (400,000 ft^2). This is a difference worthy of being addressed. However, it is smaller than the difference of all impacts (excluding ODP) between these two models—2-8 times for EP and GWP, respectively—which may indicate that that 1) at the price per m^3 set in the USEEIO bridge, impacts are not as high as those from the equivalent ecoinvent model, and 2) the height selected, 36 ft (11 m), does not magnify this difference despite being a value for new, high warehouse buildings [73].

One approach to realign USLCI+USEEIO results with those from ecoinvent would be to use the area reported by Ref [78] as part of the m^3 to unit conversion used in the USEEIO bridge. However, this ignores technological changes of the past 25 years both in terms of cell manufacture, and cell efficiency. If the ES Foundry plant is expected to produce 6 GW/year of cells with efficiencies between 22.8 % to 23.6 % [79], only 1.55e-9 factory/m^2 cell (1.00e-12 factory/m^2 cell) is needed (see Equation 2 through Equation 5). After considering the different sizes of the plant Ref. [75] and the ES Foundry, the latter requires 4.6 times less area per m^2 of cell. Therefore, rather than modifying the USEEIO bridge, the representative model for cell production should be modified.

$$\frac{3\ GW}{year} = 3 \cdot \frac{10^9 W}{year} \qquad \textbf{Equation 2}$$

$$\frac{22.8+23.6}{2} = 23.2\%\ efficiency = \frac{232W}{m^2} \qquad \textbf{Equation 3}$$

$$\frac{\frac{3GW}{year} \cdot \frac{25\ years}{factory\ lifetime}}{\frac{232W}{m^2}} = \frac{646{,}551{,}724\ m^2\ of\ cells}{factory} \qquad \textbf{Equation 4}$$

$$\frac{1\ factory}{646{,}551{,}724\ m^2\ of\ cells} = \frac{1.55 \cdot 10^{-9} factory}{cell} \qquad \textbf{Equation 5}$$

The effects of this adjustment are presented on Table 10. The almost fivefold decrease in the plant area required led to modest reductions in impacts, and these reductions decrease in importance moving down the production chain. Nevertheless, a 1 % to 2 % reduction of impacts for the whole photovoltaic system is not insignificant and highlights the importance of infrastructure and capital goods in the impacts of manufactured products. Additionally, it stresses the importance of interconnections across the production chain, including how moderately small changes in one stage can still have a noticeable effect several stages downstream.

Table 10 Effect on impacts of the update of units of photovoltaic cell plant required per m^2 of cell

	GWP	EP	AP	POCP	ODP
Cell	-7.4%	-1.3%	-7.0%	-5.6%	-8.9%
Panel	-4.3%	-1.2%	-3.7%	-3.6%	-6.2%
System	-1.8%	-1.0%	-1.6%	-1.9%	-1.9%

5.3.5. Overall gap filling analysis

In total, 42 bridges to USEEIO were developed (Table 3), addressing at least some of the identified gaps, using USEEIO bridge processes, which are based on I-O data representing an entire sector of the U.S. economy.

Table 11 shows the impacts attributed in Ref. [18, 19] to the data gaps "identified" are generally and in relative terms higher than the impacts "filled" by the use of USEEIO bridge processes. This indicates the bridge processes used here did not generate as much impact as the equivalent unit processes from the commercial repository. This general trend needs to be qualified on two counts. First, "identified" values for the photovoltaic panel and its components are for the specific stage in the production chain while "filled" values include bridge processes from all previous stages in the production chain. For example, "identified" values for the cell are for gaps in the production of the cell alone, while "filled" includes the data gaps for the cell, wafer, Single-Si, Solar Si, and metallurgical grade Si, which might explain the higher contribution of gaps to GWP in Cell "filled". The other is that for two impact categories—ODP and MIN—this general trend is not often true, indicating USEEIO bridges usually generate more impact in these two categories than the unit processes equivalent, as it has been observed for ODP in the previous Subsections.

Table 11 Relative contribution of impacts from data gaps identified and filled

		GWP	EP	AP	POCP	ODP	WATER	MIN	CEDr	CED n-r
System	Identified	41 %								
	Filled	47%	19%	29%	24%	84%	3%	55%	16%	0%
Panel[1]	Identified	18%	8%	33%	25%	5%	11%	14%	39%	17%
	Filled	12%	4%	9%	7%	55%	1%	32%	2%	0%
Cell[1]	Identified	8%	9%	13%	15%	59%	7%	85%	5%	6%
	Filled	11%	2%	7%	4%	64%	2%	70%	1%	2%
Wafer[1]	Identified	6%	3%	10%	7%	9%	5%	15%	4%	6%
	Filled	4%	1%	3%	1%	33%	1%	17%	0%	0%
Single Si[1]	Identified	26%	79%	30%	26%	67%	26%	27%	13%	4%
	Filled	1%	1%	98%	17%	0%	0%	1%	0%	0%
Solar Si[1]	Identified	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Filled	0%	2%	0%	0%	3%	0%	1%	0%	0%
Mg Si[1]	Identified	7%	1%	3%	5%	1%	1%	4%	57%	1%
	Filled	1%	5%	1%	0%	15%	1%	1%	0%	1%
Inverter	Identified	91%	94%	97%	99%	94%	94%	91%	87%	92%
	Filled	91%	96%	79%	69%	99%	19%	97%	81%	0%
Microinverter	Identified	79%	86%	90%	92%	83%	87%	85%	57%	81%
	Filled	70%	82%	49%	45%	95%	6%	95%	42%	0%
Electric	Identified	74%	97%	97%	24%	88%	90%	84%	90%	56%
	Filled	63%	46%	53%	34%	66%	50%	68%	39%	45%
Mounting	Identified	9%	7%	10%	10%	8%	9%	7%	15%	10%
	Filled	0%	0%	0%	0%	3%	0%	0%	0%	0%

		GWP	EP	AP	POCP	ODP	WATER	MIN	CEDr	CED n-r
Optimizer	Identified	95%	97%	98%	98%	97%	96%	95%	97%	94%
	Filled	77%	90%	71%	61%	99%	60%	100%	67%	68%
Recycling	Identified	73%	14%	80%	9%	16%	4%	11%	3%	4%
	Filled	47%	19%	29%	24%	84%	3%	55%	16%	0%

Note: 1) Data gaps for photovoltaic panels and their components were identified for the individual stage in Ref. [19], but data gaps filled here include all those previous stages. 0 % indicates the difference is less than 0.5 %. 3) WATER: Water resources, MIN: Mineral resources, CED: cumulative energy demand, r: renewable, n-r: non-renewable, MG: Metallurgical Grade

These results might be indicative that in general terms and apart from ODP and MIN, USEEIO impacts are lower than what could have been expected from process data. They are nevertheless only a small subset of processes, and might not indicate that overall, the impacts of USEEIO processes are systematically lower than those from unit processes from a commercial database. The case where this can be said to be generally true is for those processes with a direct emission related to an impact category—e.g., CH_3Cl_3 in $Si(CH_3)_2Cl_2$ production. Although it would be beneficial to use USEEIO bridges wherever data gaps exist, it is worth noticing they do not reflect the specific impacts of a particular production process, but of a whole industrial sector. For that reason, USEEIO bridges will likely underrepresent at least some of the impacts of the product they are linked to. In summary, USEEIO provides a valuable short-term solution to populate data gaps to account for missing process-level data, but care should be taken in interpreting results because of potential risk for systematically underestimating the impacts of specific processes throughout a production chain.

5.3.6. Uncertainty

ISO 14044 requires an analysis of uncertainty "for studies intended to be used in comparative assertions intended to be disclosed to the public" [7]. Comparative assertions are commonly understood as comparisons between products, and not between models of the same products developed with alternative datasets as done in this report. For that reason, an uncertainty analysis is not required for this project. In addition, models developed for this project do not include uncertainty to remain consistent with bridge processes in other repositories of the Federal LCA Commons that do not report uncertainty of their exchanges [22]. This is due to the nature and purpose of bridge processes, which are a simplified alternative for filling a data gap (i.e., a proxy input-output process representing a complete unit process). A detailed quantification of their uncertainty is out of scope of the processes in the Federal LCA Commons. Therefore, uncertainty is not quantified herein this report.

Nevertheless, a discussion of the sources of uncertainty can help contextualize the results obtained through Section 5.3. In LCA modeling, there are three main sources of uncertainty, [80, 81]:

- Model uncertainty
- Uncertainty due to modeler choices
- Parameter uncertainty

Central to model uncertainty of bridge processes is the USEEIO repository. Documents describing this repository do not discuss uncertainty and, therefore, its effect on the bridge processes developed cannot be assessed. Another source of model uncertainty is unit conversion. This is shown in Section 5.3.4 when discussing the relationship between volume and units of solar cell factory, and how they relate to area of solar cell produced. Although this case may be an extreme outlier, it is an important reminder of the need for appropriate unit conversions.

An example of uncertainty due to modeler choices in bridge processes to USEEIO is the selection of the “target flow,” the industrial sector in the USEEIO repository selected as a proxy for the manufacturing of the product whose impact is of interest. Due to the high-level nature of the USEEIO sectors, the selection is often straightforward. One example is the production of “Electrolytic capacitor; at plant; >2 cm height,” which is likely well represented by the USEEIO sector “Electronic capacitors, resistors, coils, transformers, connectors and other components (except semiconductors and printed circuit assemblies).” Other cases, however, may not be as straightforward. Selecting a sector that does not represent the intended production process would lead to the use of different emission factors. Table 12 highlights this scenario by comparing the impacts of organic and inorganic chemicals in USEEIO, showing absolute differences between 39 % to 172 % depending on the impact category.

Table 12 Comparison between inorganic and organic chemicals in USEEIO

	GWP	**EP**	**AP**	**POCP**	**ODP**	**WATER**	**MIN**	**CEDr**	**CED n-r**
Impact per $	kg CO_2 eq	kg N eq	kg SO_2 eq	kg O_3 eq	kg CFC11 eq	kg	kg	MJ	MJ
Inorganic	8.7E-1	5.6E-4	1.7E-3	2.3E-2	2.6E-7	3.9E+1	5.7E+0	1.1E+0	1.6E+1
Organic	1.6E+0	4.4E-3	3.6E-3	3.5E-2	1.8E-6	9.8E+1	4.2E-1	6.7E-1	2.6E+1
Avg. of difference	61%	155%	72%	39%	149%	87%	172%	49%	50%

Finally, parameter uncertainty is often linked to choices for bridge processes to USEEIO. As mentioned in Section 2, the price per unit is the key parameter of USEEIO and its bridge processes. As a result, source selection is equated with the choice of a key parameter. Since impacts scale linearly with cost, selecting a price twice as high will result in doubling impacts. Depending on the source used, parameter uncertainty could be quantified. For example, for a given scale of nitrogen production, the values available on Ref. [55], could be used to develop a triangular function for the price. However, for many of the sources used here, only a single value for the latest quarter is publicly available. This is deemed sufficient, as LCI data are typically point estimates [82]. Collecting additional historical data, or collecting prices from multiple sources is beyond the scope of this project, but could be done if a more precise bridge process is desired. However, the effort needed for this data collection and the precision gained from it must be balanced with those of collecting process data to develop more representative unit processes.

6. Conclusion

Using USEEIO is a readily accessible way to fill data gaps in other FLCAC repositories. However, it is not a substitute for developing process units for those same data gaps because USEEIO is data representing an entire economic sector and not the specific process it is representing in the LCA model. Thus, it should not be expected to lead to the same estimated impacts obtained by using other repositories. To maximize the usefulness of bridging USLCI—or any other repository—to USEEIO, the following recommendations are suggested.

- Whenever possible, use market average prices for industrial buyers. USEEIO bridges are sensitive to the price per unit (e.g., kg). Prices for products, such as chemicals, can vary widely depending on the scale at which they are purchased, among other factors. Using retail prices may be occasionally necessary, but it may result in overestimating impacts (e.g., $POCl_3$ for the photovoltaic cell).
- Appropriate price selection requires expert knowledge of the products for which a bridge is built. Otherwise, overestimations and underestimations might occur (e.g., electronics in the inverter).
- Unit conversions, as in any LCI, are critical in USEEIO bridges when required. Beyond the mathematical conversion (e.g., tons to kg) it is necessary to evaluate whether the "unit" in the $/unit identified is functionally equivalent to the unit referenced in the inventory (e.g., photovoltaic cell plant).

From an analytical perspective, having all five ISO 21930 impact categories normalized side by side drew attention to the different behavior of models built using commercial datasets (i.e., ecoinvent) and USLCI+USEEIO. In general, processes from the commercial repository have much higher EP impacts than the alternative, while bridges to USEEIO have higher ODP impacts. This conclusion is solely based on the models assessed here for photovoltaic systems and might not be indicative of major differences in the repositories. These broader differences could be evaluated in a more systematic way to better assess the effect of combining and/or comparing repositories.

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Appendix A. List of Symbols, Abbreviations, and Acronyms

AP
Acidification potential

CED
Cumulative energy demand

CFC
Chlorofluorocarbon

CONSIS
CONtribution analySIS (Pythin code)

DPGME
Dipropylene glycol monomethyl ether

EP
Eutrophication potential

EPA
U.S. Environmental Protection Agency

ERG
Eastern Research Group

EVA
Ethylene vinyl acetate

FEDEFL
Federal LCA Commons Elemental Flow List

FLCAC
Federal LCA Commons

GWP
Global warming potential

IC
Integrated circuit

IEA
International Energy Agency

IO
Input Output

ISO
International Standards Organization

LCA
Life Cycle Assessment

LCD
Liquid Crystal Display

LCI

Life Cycle Inventory

MIN
Mineral resources (FEDEFL Inventory Indicator)

NAICS
North America Industry Classification System

ODP
Ozone depletion potential

POCP
Photochemical oxidant creation

PPI
Producer Price Index

PV
Photovoltaic

PVF
Polyvinyl fluoride

PVPS
Photovoltaic Power Systems

SMD
Surface mounted device

USEEIO
U.S. Extended Environmental Input Output

USLCI
U.S. Life Cycle inventory

UUID
Universal Unique Identifier

WATER
Water resources (FEDEFL Inventory Indicator)

Appendix B. Supplemental Materials

B.1. Code

Two pieces of Python code were built and used for creating bridge processes to USEEIO, processing models in bulk, and facilitating the analysis presented here. Instructions for their use can be found in Section 4:

- Bridge addition USEEIO: Export USEEIO bridge processes built on Excel to openLCA.
- CONSIS: Runs in openLCA the indicated processes for the impact assessment methods selected and export their results to Excel. It has an option to only offer first level results—the impacts of those processes—or an in-depth contribution analysis.

The code for these resources can be found in [INSERT REFERENCE HERE]

B.2. Workbooks

The following workbooks were built for and used during the data gap analyses presented here and were made available at [INSERT REFERENCE HERE].

- USEEIO bridges: Helps create USEEIO bridge processes. The instruction for its use can be found in Section 4
- Comparison template: Extracts data from multiple Excel files generated through CONSIS and saves internally for future data processing. The instructions for this template are below. With this template the following workbooks were created:
  - System comparison (Two versions, one for Fig 1, another for Fig 2)
  - Inverter comparison
  - Panel comparison
  - Cell comparison

All these workbooks share the following worksheets. The first two are needed to export data from other workbooks to the comparison workbook in question and freeze the results.

- 'Settings' indicates where to extract data by specifying a FolderPath, a FileName, and two tables: varMappingTable, and varUnitTable. VarMappingTable relies on sheets on the target file to follow the CONSIS naming convention, PxMyCz, where P stands for process, M for method, and C for Category, and x, y, and z are the numbers of the respective process, method, and category to be extracted. It also contains columns for the name given to the impact category, and the order in which they are to be copied, which does not need to match that of the original file. Finally, varUnit table links each impact category—whose name must match the one in varMappingTable—with its respective units. In addition, there are two buttons, "Update results" and "Save results snapshots". The first one refreshes the table in 'LCA_Results' with the selected data. The second copies and freezes the results of "LCA_Results" Into a sheet with the name in FileName.

- 'LCA_Results' Contains a table with the last results extracted, which might not coincide with those defined in 'Setting' if it has not been updated. To do so click anywhere in the table, select the "Query" tab, and from the options available "Refresh". Alternatively, run the UpdateResults macro, or simply click on the appropriate button in 'Settings'.

Worksheets generated and frozen can be kept with their names, or shortened for convenience, as was done in the existing workbooks. The following sheets systematize and simplify the comparison of those results.

- 'Reference' should contain a column with the short names of the processes as they should appear in a figure/table: electricity, diesel, etc. and as many columns as models whose process have different names, usually one for Ecoinvent and one for USLCI. Columns need to be manually reorganized so all processes are properly aligned—e.g., that "Electricity", "market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U", and "Electricity Bridge; Building Systems to U.S. Electricity Baseline" are all in the same row.
- 'Helper' consists of three columns A, B, and C. A contains the name of the model as it should appear on the tables or figures. B has the reference column. This is, the column on 'Reference' where the appropriate names of the process appear. On C, the data Sheet name should be specified. This is, the name of the sheet where the data can be found.

These two sheets are the basis of the following formula, which is us used in the 'Comparison' and 'Comparison sources 'sheets. It relies on processes in column C having the same short names as in 'Reference', and the header (in this example in D1) being of the form NameModel Impact category.

```
=LET(
  _header, D$1,
  _process,$C2,
  _modelName, IFERROR(TRIM(LEFT( _header, FIND(" ", _header)-1)), ""),
  _impactCat, IFERROR(TRIM(RIGHT(_header, LEN(_header)-FIND(" ", _header))), _header),

  _refCol, XLOOKUP(_modelName, Helper!$A:$A, Helper!$B:$B, "Err"),
  _sheetName, XLOOKUP(_modelName, Helper!$A:$A, Helper!$C:$C, "Err"),

  IF(OR(_refCol="Err", _sheetName="Err"), "Check Model Name in Header/Helper Table",

  LET(
    _modelProcessName, XLOOKUP(_process, Reference!$B:$B, INDIRECT("Reference!" & _refCol & ":" & _refCol), "Process not in Ref"),
```

```
    _impactDataRange, INDIRECT("'" & _sheetName & "'!A:Z"),
    _impactHeaderRange, INDIRECT("'" & _sheetName & "'!1:1"),
    _processNameRange, INDIRECT("'" & _sheetName & "'!A:A"),

    _colNum, IFERROR(
      MATCH(_impactCat & "*Total result*", _impactHeaderRange, 0),
      MATCH(_impactCat & "*Total Impact*", _impactHeaderRange, 0)
    ),
    _impactColumn, IF(ISNA(_colNum), "Impact Header Not Found", INDEX(_impactDataRange, , _colNum)),

    IF(OR(ISERROR(_modelProcessName), ISERROR(_impactColumn)), "Check Names/Headers",
      XLOOKUP(_modelProcessName, _processNameRange, _impactColumn, "Process Not Found in Sheet")
    )
  ))
)
```

- ‘Comparison sources’ includes the impacts for three models: Ecoinvent and USLCI+USEEIO, with and without gaps. In addition the relative contribution of each process to the first two is calculated to identify priority processes—those with at least one impact over 1 %. This criterion is used in the following worksheet to build the figures included in this report:
- ‘Comparison short’ combines the impacts of all those processes with less than 1 ` in all categories in a group called “Others” while keeping the rest of the processes. Individual processes and “others” are then split between their contribution related to gaps filled with USEEIO, and other impacts.

The last sheet facilitates the creation of figures such as the ones shown in this report.

- ‘ColorKeys’ contains a Table, “ColorKeyTable” that is linked to a macro. “FormatStackedChartSeries”. The table contains three columns: Category, color, and Pattern. In the first one, the categories to be shown in the figure should be listed. In the second, the number of the color should be added. To facilitate conversion from RGB color codes, a formula GetRGB(x,y,z) was created, where x, y, and z are the codes for Red, Green, and Blue, respectively. Finally, the “Pattern” column should reflect the desired patters. For example, xlPatterSolid was used for the “non-gap processes” and xlPatternDown for the “data gap processes”.