Case study: modeling the life cycle of a PV system with HiQLCD and ecoinvent databases

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I. Goal and Scope

Goal

The goal of the study is to assess the environmental impacts of a photovoltaic system produced in China, Shanxi province, later transported to Germany for the use and end-of-life phases, when it is transported to a facility in Münster for recycling while the non-recyclable fraction is sent to Stuttgart/Münster combined heat and power plant for incineration.

The system includes a PV module, its mounting structure and other system components, including a PV inverter and junction box.

This LCA is carried as an internal study with the purpose of using the HiQLCD database and the results are calculated with the Environmental Footprint 3.1 (EF3.1) method.

The study is performed using openLCA software v.2.5.0, the Chinese database HiQLCD (High-Quality Life Cycle Database), to model the production of the PV system and the transportation to Rotterdam harbor, and ecoinvent 3.11, used to model the transportation from Rotterdam harbor to Berlin, the use phase and the end-of-life.

Since the study is based on ecoinvent and HiQLCD databases, the first step was to upload the two databases in the software, so that datasets from both could be used in the appropriate life cycle stage.

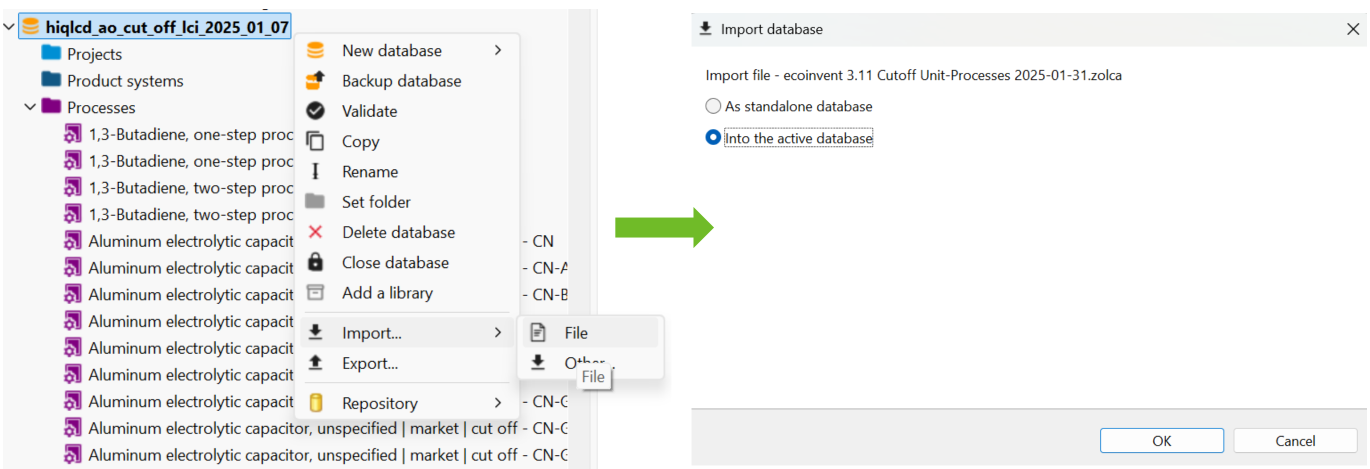


Figure 1 – Representation of the process of importing a database (ecoinvent) in an existing database (HiQLCD).

Functional Unit

The functional unit is defined as 1 kWh of electricity generated by the slanted-roof photovoltaic system over its operational lifetime, 25 years.

System boundaries

The system boundary is defined as cradle-to-grave, thus considering all the life cycle of the PV system:

- Raw material supply
- Trasport to factory
- Manufacturing
- Transport to Germany
- Use phase
- Transport to recycling facility in Münster
- Transport of the non-recyclable fraction to Stuttgart/Münster combined heat and power plant

The detail of the database used for each life cycle stage as well as the country where the same takes place is represented in figure 2.

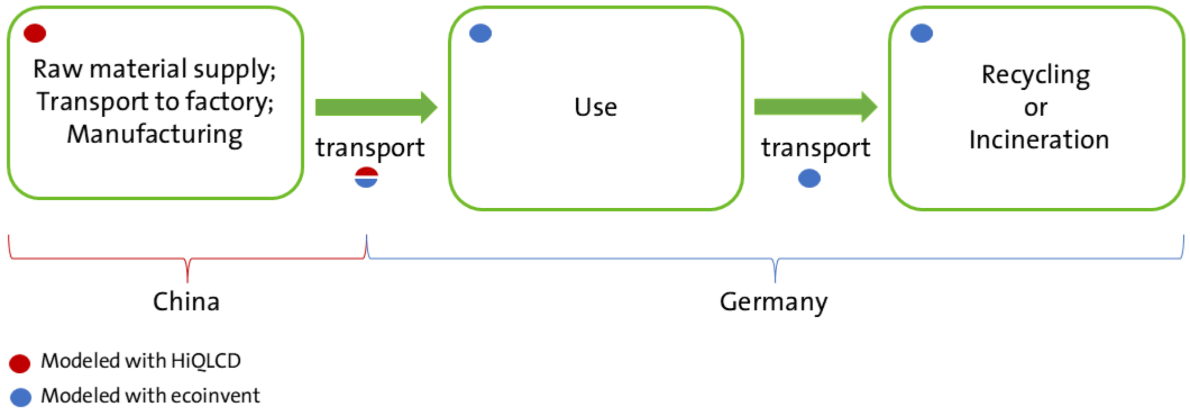


Figure 2 – System boundaries of the system under study and highlighting of the database used for each life cycle stage

LCIA Method

The LCIA method chosen for this study is the Environmental Footprint 3.1, and the categories assessed in this study are all those proposed by the method:

- Acidification
- Climate change
- Climate change: biogenic
- Climate change: fossil
- Climate change: land use and land use change
- Ecotoxicity: freshwater
- Ecotoxicity: freshwater, inorganics
- Ecotoxicity: freshwater, organics
- Energy resources: non-renewable
- Eutrophication: freshwater
- Eutrophication: marine
- Eutrophication: terrestrial
- Human toxicity: carcinogenic
- Human toxicity: carcinogenic, inorganics
- Human toxicity: carcinogenic, organics
- Human toxicity: non-carcinogenic
- Human toxicity: non-carcinogenic, inorganics
- Human toxicity: non-carcinogenic, organics
- Ionizing radiation: human health
- Land use
- Material resources: metals/minerals
- Ozone depletion
- Ozone depletion
- Photochemical oxidant formation: human health
- Water use

II. Life Cycle Inventory

The Chinese database HiQLCD (cut-off) was used to model the production phase of the PV system, taking place in Shanxi province in China, and the transportation to Europe until Rotterdam harbor. On the contrary the processes taking place from the Rotterdam harbor onward have been modeled using ecoinvent 3.11 (cut-off).

Below are reported the model graphs representing the life cycle of the PV system until the use phase (figure 3) and from the use phase to the end-of-life (figure 4).

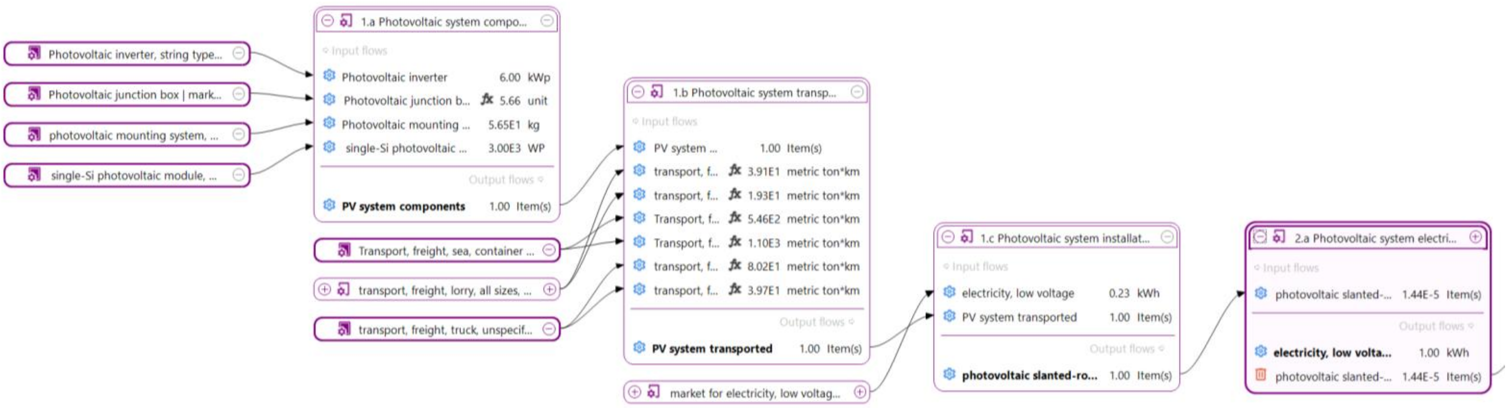


Figure 3 - openLCA model graph representing the upstream processes of the PV system until the use phase

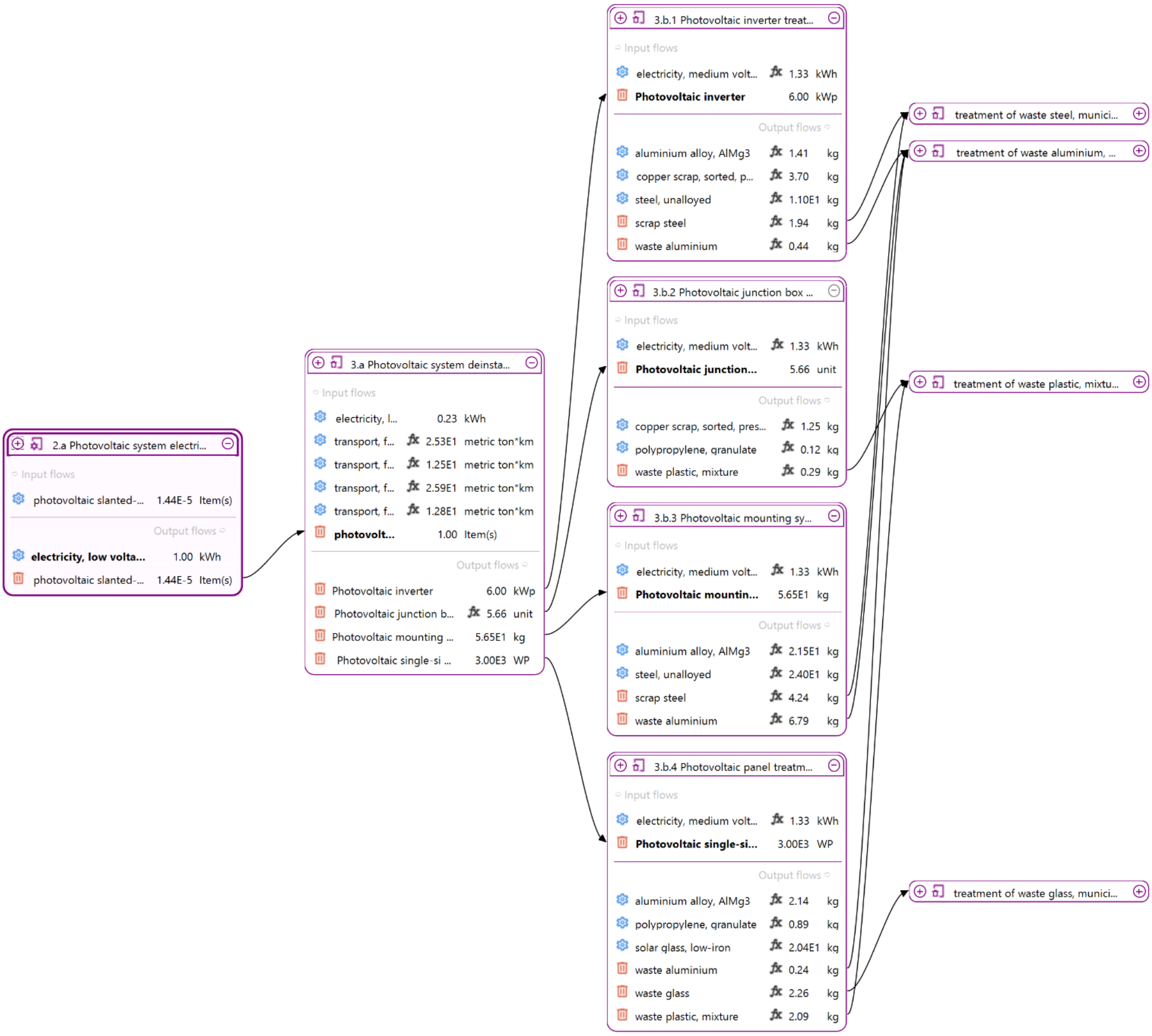


Figure 4 - openLCA model graph representing the processes of the PV system from the use phase until the end-of-life.

The life cycle stages of the photovoltaic system were modeled as reported in the following paragraphs.

1. Upstream processes

1.a Photovoltaic system components sourcing

This process represents the sourcing of the components for the photovoltaic system, namely photovoltaic inverter, photovoltaic junction box, photovoltaic mounting system and single-Si photovoltaic module, including their production in China. Indeed, the flows related to the components include the "main raw materials, energy, atmospheric emissions, and waste from the production process" and the "transport from the gate to the point of consumption", as reported in the description of the provider of the flow. Whenever possible, specific data from the Shanxi region were used, otherwise data from the more general Chinese national provider (CN) were considered.

As the Chinese database is characterized by the use of system processes, it was not possible to identify a process describing the quantities of each component needed for the fabrication of a whole photovoltaic system. Therefore, the ecoinvent process "photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | U – RoW" was taken as reference to obtain such amounts. In order to do so, the values related to flows from the Chinese database were duly harmonized taking into account the specificities of the HiQLCD database, as reported in table 1.

Table 1- Harmonization of the HiQLCD flows with the ecoinvent database.

Ecoinvent flow	Amount	HiQLCD modified flow	Amount	Provider	Assumptions / rationale
Inverter, 2,5 kW	2.4 units	Photovoltaic inverter	6.0 kWp	Photovoltaic inverter, string type, market - CN	*A linear downscaling to 6 kWp was assumed.
Photovoltaic mounting system, for slanted-roof installation	21.429 m^2 (inferred)	Photovoltaic mounting system	56.5447 kg	Photovoltaic mounting system, market - CN-SX	**Original flow assumed to represent 21,429 m^2. Conversion to mass was done using summed weight of steel and aluminum per m^2 in ecoinvent + Increasing the efficiency. Packaging excluded to focus on structural materials only.

Table 1- Harmonization of the HiQLCD flows with the ecoinvent database

Photovoltaic panel, single-Si wafer	22.071 m^2	single-Si photovoltaic module, mono-facial	3000 WP	single-Si photovolaic module, market - CN	***Adapted from item count to capacity-based input. Assumed equivalence with 3kWp system.
Photovoltaics, electric installation for 3kWp module	1 unit	Photovoltaic junction box	3000/530 = 5.66 units	Photovoltaic junction box, market - CN	****Estimated junction box contribution per watt; converted based on PV capacity.

* **Inverter – Flow Adjustment and Assumptions**

In the original ecoinvent 3.11 dataset, the input *"inverter, 2,5 kW"* was used, with a quantity of 2,4 units, corresponding to a total installed capacity of 6 kW. The dataset represents a small residential inverter, weighing approximately 18,5 kg per unit. As inverter lifetimes are typically shorter than those of PV panels, often estimated around 12–15 years, a single 3 kW inverter used continuously over 25–30 years would likely require replacement at mid-life, justifying the 6 kW-equivalent impact allocation in the LCI. However, it is important to note that the Chinese inverter dataset refers to a string inverter of approximately 110 kW capacity and 110 kg in weight, typically used in larger-scale PV installations. Although the Chinese inverter dataset is based on a larger-scale system, a linear approximation was applied to model the 6 kWp capacity, in the absence of more granular inverter options. The difference in scale and design (residential vs. commercial/industrial) may affect the material intensity and environmental impact profile, but was deemed as conservative and therefore appropriate for the aim of the study.

** **Mounting System – Flow Adjustment and Assumptions**

In the original ecoinvent dataset (*"photovoltaic mounting system, for slanted-roof installation"*), the input was recorded as 21.429 units. Based on the dataset documentation (*"Production of the additional components necessary for the mounting of 1 m^2 PV panel"*), this was interpreted as 21.429 m^2 of photovoltaic panel mounting infrastructure.

In contrast, the Chinese regionalized database defines the equivalent mounting system process in kilograms (kg). To perform an appropriate a harmonization between the two datasets, a conversion was carried out based on the material composition of the mounting system per square meter, as documented in the ecoinvent inventory:

Aluminium, wrought alloy: 2.8355 kg/m²

Steel, low-alloyed, hot rolled: 1.4999 kg/m²

Total structural mass: 4.3354 kg/m²

Moreover, as Hi-QLCD database is more recent, it allows for the integration of modern photovoltaic efficiency assumptions. Based on current manufacturer specifications and literature, a conversion efficiency of 23% was used in this study. Given that a 3 kWp system with 23% efficiency corresponds to approximately 13.16 m² of panel area, the mounting system material requirement becomes:

4.3354 * 13.16 = 56.5447 kg

***Photovoltaic Module – Flow Adjustment and Assumptions**

In the original ecoinvent dataset, the photovoltaic panel input is expressed as 22,071 m² of monocrystalline silicon modules. In contrast, the Chinese regionalized database defines the same input in Wp (watt-peak). Since the modelled system represents a 3 kWp installation, the input was directly set to 3000 Wp.

This choice aligns the input with the total installed system capacity and ensures consistency with the unit structure used throughout the Chinese dataset.

****Electrical Installation – Flow Adjustment and Assumptions**

In the original ecoinvent dataset, the flow *"photovoltaics, electric installation for 3kWp module, at building"* is included to represent the electrical components necessary for a standard rooftop photovoltaic system. This flow is expressed as a single unit, implicitly including key elements such as cabling, connectors and the junction box required to connect the panels to the inverter and distribution system.

In the updated Chinese regionalized database, no equivalent aggregated flow was available. Instead, the most appropriate match was identified as:

"Photovoltaic junction box", expressed in number of units.

To maintain consistency with the system size (3 kWp), and assuming that one junction box is typically used per system of this size, the input was modelled as 3000/530 = 5,66 units, where 530 Wp corresponds to the typical capacity of one module in the Chinese database. This calculation assumes that each 530 Wp module includes one junction box, which aligns with typical system design where junction boxes are installed per panel or per string.

After performing the harmonization explained above, the process was modeled as per table 2.

Table 2 Process representing the sourcing of the components of the photovoltaic system taking place in China

Input			
Flow	Amount	Unit	Provider
Photovoltaic inverter	6	kWp	Photovoltaic inverter, string type | market | cut off - CN
Photovoltaic junction box	5.660377	unit	Photovoltaic junction box | market | cut off - CN
Photovoltaic mounting system	56.5447	kg	photovoltaic mounting system, unspecified | market | cut off - CN-SX
single-Si photovoltaic module, mono-facial	3000	WP	single-Si photovoltaic module, mono-facial, unspecified | market | cut off - CN
Output			
Flow	Amount	Unit	Provider
PV system components	1	Item(s)	

1.b Photovoltaic system components transportation

The process represents the transport of the photovoltaic system components from the manufacturing site in China to the installation location in Berlin (Alt-Moabit 130, 10557). The two key components considered for transport are the PV module and the mounting structure, both assumed to be produced in Taiyuan, Shanxi province (CN-SX), and shipped via Shanghai port. The flows regarding land transportation in China from Taiyuan to Shanghai harbor and sea transportation from Shanghai to Rotterdam harbor were provided by HiQCLD database, while land transportation from Rotterdam harbor to Berlin was provided by ecoinvent database.

Further details on the modeling assumptions are reported hereafter:

- PV module mass: 28 kg

- Mounting system mass: 56.545 kg
- Transport route:
  1. Road – Taiyuan to Shanghai port: 1419 km (Google Maps), using HiQLCD
  2. Sea freight – Shanghai to Rotterdam port (via Suez Canal): 19 495 km (Sea Distances), using HiQLCD
  3. Road – Rotterdam to Berlin: 691 km (Google Maps), using ecoinvent

Table 3- Process representing the transport of the PV module and mounting structure from China to Berlin

Input			
Flow	Amount	Unit	Provider
PV system components	1	Item(s)	1.a Photovoltaic system components sourcing
transport, freight, lorry, unspecified	691*0.056545	metric ton*km	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspecified | Cutoff, U - RER
transport, freight, lorry, unspecified	691*0.028	metric ton*km	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspecified | Cutoff, U - RER
Transport, freight, sea, container ship, loading 15000-20000t	19495*0.028	metric ton*km	Transport, freight, sea, container ship, loading 15000-20000t | production | cut off - CN
Transport, freight, sea, container ship, loading 15000-20000t	19495*0.056545	metric ton*km	Transport, freight, sea, container ship, loading 15000-20000t | production | cut off - CN
transport, freight, truck, China VI	0.056545*1419	metric ton*km	transport, freight, truck, unspecified, China VI | production | cut off - CN
transport, freight, truck, China VI	0.028*1419	metric ton*km	transport, freight, truck, unspecified, China VI | production | cut off - CN
Output			
Flow	Amount	Unit	Provider
PV system transported	1	Item(s)	

From the next process onward, only ecoinvent database was used, as all following life cycle stages take place in Germany.

1.c Photovoltaic system installation

The process describes the installation of the photovoltaic system once arrived in Berlin. The amount of electricity used for this phase was also taken from the ecoinvent process "photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | U – RoW", where the total amounted to 0.23kWh of low voltage electricity used. The flow is given by a process from ecoinvent database representing the German market for electricity.

Table 4 Process representing the installation of the PV module in Berlin

Input			
Flow	Amount	Unit	Provider
electricity, low voltage	0.23	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - DE
PV system transported	1	Item(s)	1.b Photovoltaic system components transportation
Output			
Flow	Amount	Unit	Provider
photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof	1	Item(s)	

2. Use phase

2.a Photovoltaic system electricity production

This process represents the production of electricity of 1 kWh of electricity from 1.44465E-5 units of the 3 kWp PV system process. This proportion reflects the assumed electricity output over the lifetime of the system and was defined following the approach proposed by Ecoinvent 3.11 and it is based on solar irradiation conditions specific to Germany.

Table 5 - Process representing electricity production from the photovoltaic system

Input			
Flow	Amount	Unit	Provider
photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof	1.44E-05	Item(s)	1.c Photovoltaic system installation
Output			
Flow	Amount	Unit	Provider
electricity, low voltage, renewable energy products	1	kWh	
photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof	1.44E-05	Item(s)	3.a Photovoltaic system deinstallation

3. End-of-life

3.a Photovoltaic system deinstallation

This process defines the deinstallation of the photovoltaic system once it reaches the end of its lifetime, equal to 25 years, and includes:

- The electricity used to deinstall the PV system, the amount of which was assumed to be the same as the quantity used during the installation phase.
- The transport from the location where it was installed in Berlin (Alt-Moabit 130, 10557) towards the recycling site in Münster (447 km). As per what was previously considered, the two key components considered for transport are the PV module and the mounting structure.
- The transport of the non-recyclable fraction from the recycling site in Münster to Stuttgart/Münster combined heat and power plant for incineration (458 km). In this case too, the two key components considered for transport are the PV module and the mounting structure.

- The outputs of the process are considered as being the four main elements identified as part of the photovoltaic system (photovoltaic inverter, photovoltaic junction box, photovoltaic mounting system, single-Si photovoltaic module).

Following this process, for each component a treatment phase was modeled.

Table 6 - Process representing the photovoltaic system deinstallation, including transport

Input			
Flow	Amount	Unit	Provider
photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof	1	Item(s)	
electricity, low voltage	0.23	kWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U - DE
transport, freight, lorry, unspecified	447*0.028	metric ton*km	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspecified | Cutoff, U - RER
transport, freight, lorry, unspecified	447*0.056545	metric ton*km	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspecified | Cutoff, U - RER
transport, freight, lorry, unspecified	458*0.028	metric ton*km	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspecified | Cutoff, U - RER
transport, freight, lorry, unspecified	458*0.056545	metric ton*km	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspecified | Cutoff, U - RER
Output			
Flow	Amount	Unit	Provider
Photovoltaic inverter	6	kWp	3.b.1 Photovoltaic inverter treatment

Table 6 - Process representing the photovoltaic system deinstallation, including transport

Photovoltaic junction box	3000/530	unit	3.b.2 Photovoltaic junction box treatment
Photovoltaic mounting system	56.5447	kg	3.b.3 Photovoltaic mounting system treatment
Photovoltaic single-si module	3000	WP	3.b.4 Photovoltaic panel treatment

Photovoltaic system components treatment

The treatment of each component of the photovoltaic system was modeled separately. As previously said, it was assumed that the component is disassembled and a recyclable part is sent to recycling in Münster where the later identified non-recyclable part is followingly sent to another facility for incineration. It was assumed a total of 5.33 kWh to disassemble the whole photovoltaic system, so for each of the four treatment processes modeled it was assumed a quantity of energy equal to 1.33 kWh. No other resources were considered, in order to have a simplified but yet representative process. In order to maintain coherence with the other transport phases, only the mounting system and the PV module were considered in the modeling. Moreover, regarding the materials resulting from the disassembling of the components, only the main ones were considered.

3.b.1 Photovoltaic inverter treatment

In order to establish the composition of the inverter, as no insights were given in the description of the process for the inverter production in the HiQLCD database, the corresponding ecoinvent process was considered (“Inverter, 2,5 kW”). The weight was assumed being 18.5 kg and the main components were identified as steel (70%), copper (20%) and aluminum (10%). The recyclability rate was considered the same as for the processes above, so respectively 85% for steel, 100% for copper and 76% for aluminum.

Table 7 - Process representing the photovoltaic inverter treatment

Input			
Flow	Amount	Unit	Provider
Photovoltaic inverter	6	kWp	
electricity, medium voltage	1.3325	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - DE
Output			
Flow	Amount	Unit	Provider
waste aluminium	18.5*0.24*0.1	kg	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
scrap steel	18.5*0.15*0.7	kg	treatment of waste steel, municipal incineration | waste steel | Cutoff, U - Europe without Switzerland
copper scrap, sorted, pressed	18.5*0.2	kg	
steel, unalloyed	18.5*0.85*0.7	kg	
aluminium alloy, AlMg3	18.5*0.76*0.1	kg	

3.b.2 Photovoltaic junction box treatment

In order to establish the composition of the junction box, as no insights were given in the description of the process for the junction box production in the HiQLCD database, the corresponding ecoinvent process was considered ("Photovoltaics, electric installation for 3kWp module"). The weight of the junction box was assumed being 0.22kg and the two main components were identified as polypropylene and copper. Namely, considering the proportion of the quantities of such materials in the ecoinvent process, it was established that 1/3 of the composition was polypropylene (PP) and 2/3 were copper. As per the recyclability rate, it was considered that 30% of the PP is recycled, while for copper the percentage is equal to 100%.

Table 8 - Process representing the photovoltaic junction box treatment

Input			
Flow	Amount	Unit	Provider
Photovoltaic junction box	5.660377	unit	
electricity, medium voltage	5.33*0.25	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - DE
Output			
Flow	Amount	Unit	Provider
copper scrap, sorted, pressed	0.22*5.66038	kg	
polypropylene, granulate	0.22*5.66038*0.33*0.30	kg	
waste plastic, mixture	0.22*5.66038*0.33*0.70	kg	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW

3.b.3 Photovoltaic mounting system treatment

In the description of the process rom HiQLCD database "photovoltaic mounting system, unspecified | production | cut off" it is reported: "[...] the PV mounting structure [...] is the arithmetic mean of the following: the datasets for "PV mounting system, aluminum alloy" and "PV mounting system, galvanized carbon steel." So, it was assumed that 50% is aluminum and 50% is steel. The recyclability rate was established as 76% for aluminum and 85% for steel.

The treatment process was therefore modeled as follows:

Table 9 - Process representing the photovoltaic mounting system treatment

Input			
Flow	Amount	Unit	Provider
Photovoltaic mounting system	56.5447	kg	
electricity, medium voltage	5.33*0.25	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - DE

Table 9 - Process representing the photovoltaic mounting system treatment

Output			
Flow	Amount	Unit	Provider
waste aluminium	56.5447*0.50*0.24	kg	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
scrap steel	56.5447*0.50*0.15	kg	treatment of waste steel, municipal incineration | waste steel | Cutoff, U - Europe without Switzerland
steel, unalloyed	56.5447*0.50*0.85	kg	
aluminium alloy, AlMg3	56.5447*0.50*0.76	kg	

3.b.4 Photovoltaic panel treatment

For the treatment and the composition of the photovoltaic panel, a publication from the Institute for Sustainable Futures from 2019 was taken into account. According to this source, it is reported that "A typical crystalline silicon PV panel contains about 76% glass (panel surface), 10% polymer (encapsulant and back-sheet foil), 8% aluminum (frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (e.g. tin and lead)." Therefore, for the purpose of this study only glass, polymers (polypropylene was considered) and aluminum were considered, and their quantity was adjusted in order to account for 100% of the composition. As per the recyclability rate, in the study it is reported that glass and aluminum have a high recycle rate, around 90%. Regarding polymers, no specific values were indicated, so the previously considered recyclability rate of 30% was considered.

Table 10 - Process representing the photovoltaic inverter treatment

Input			
Flow	Amount	Unit	Provider
Photovoltaic single-si module	3000	WP	
electricity, medium voltage	1.3325	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - DE

Table 10 - Process representing the photovoltaic inverter treatment

Output			
Flow	Amount	Unit	Provider
waste aluminium	2.38*0.10	kg	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
waste plastic, mixture	2.98*0.70	kg	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW
waste glass	22.64*0.10	kg	treatment of waste glass, municipal incineration | waste glass | Cutoff, U - GLO
polypropylene, granulate	2.98*0.3	kg	
aluminium alloy, AlMg3	2.38*0.90	kg	
solar glass, low-iron	22.64*0.90	kg	

III. Life cycle impact assessment

Normalized and weighted analysis

In order to identify the most relevant impacts connected to the life cycle of the PV system, it was necessary to assess all the impact categories proposed by the LCIA method Environmental Footprint 3.1. After that, a normalization and weighting of the results was performed.

The reference units of the impact categories are reported hereafter in table 11.

Table 11 – Reference units of the impact categories under study.

Impact category	Reference unit
Acidification	mol H+-Eq
Climate change	kg CO2-Eq
Ecotoxicity: freshwater	CTUe
Energy resources: non-renewable	MJ
Eutrophication: freshwater	kg P-Eq
Eutrophication: marine	kg N-Eq
Eutrophication: terrestrial	mol N-Eq
Human toxicity: carcinogenic	CTUh

Table 11 – Reference units of the impact categories under study.

Human toxicity: non-carcinogenic	CTUh
Ionising radiation: human health	kBq U235-Eq
Land use	dimensionless
Material resources: metals/minerals	kg Sb-Eq
Ozone depletion	kg CFC-11-Eq
Particulate matter formation	disease incidence
Photochemical oxidant formation	kg NMVOC-Eq
Water use	m3 world Eq deprived

Hereafter are reported the table of the normalized and weighted results where the green highlighted percentages are those that together reach 80% of the total contribution. This rule (Pareto principle) was followed to identify the impact categories with the highest impact.

The standard deviation values were obtained by running Monte Carlo simulation. Before performing it, uncertainty based on a logarithmic normal distribution was associated to uncertain relevant parameters such as:

- The amount of electricity used during the installation and deinstallation phase as well as in the recycling and treatment phase of the PV components. Indeed, such value was estimated or taken from literature, but it may vary significantly depending on the situation and facility.
- The amounts of recycled material and waste deriving from the treatment of the PV components. The percentages of recyclability are indeed uncertain and variable, as well as the composition of the different PV components.

Table 12 - Results of the impact analysis with the Monte Carlo simulation. The value in green is the one that satisfied the Pareto rule.

Impact category	Result	Standard deviation	Normalized	Weighted	Contribution
Acidification	2.65E-04	1.23E-07	4.77E-06	2.96E-07	0.9%
Climate change	3.44E-02	5.78E-13	4.55E-06	9.58E-07	3.0%
Ecotoxicity: freshwater	3.19E-01	6.59E-13	5.62E-06	1.08E-07	0.3%
Energy resources: non-renewable	4.98E-01	1.92E-05	7.66E-06	6.38E-07	2.0%

Table 12 - Results of the impact analysis with the Monte Carlo simulation. The value in green is the one that satisfied the Pareto rule.

Eutrophication: freshwater	1.18E-05	3.28E-08	7.35E-06	2.06E-07	0.6%
Eutrophication: marine	4.10E-05	1.98E-14	2.10E-06	6.20E-08	0.2%
Eutrophication: terrestrial	4.77E-04	3.65E-08	2.70E-06	1.00E-07	0.3%
Human toxicity: carcinogenic	1.95E-11	3.55E-07	1.13E-06	2.41E-08	0.1%
Human toxicity: non-carcinogenic	7.44E-10	1.01E-14	5.78E-06	1.06E-07	0.3%
Ionising radiation: human health	1.49E-03	1.93E-05	3.52E-07	1.76E-08	0.1%
Land use	1.72E-01	2.43E-10	2.10E-07	1.67E-08	0.1%
Material resources: metals/minerals	2.31E-05	2.12E-04	3.64E-04	2.75E-05	85.2%
Ozone depletion	3.47E-09	3.33E-04	6.63E-08	4.18E-09	0.0%
Particulate matter formation	2.31E-09	1.25E-07	3.89E-06	3.48E-07	1.1%
Photochemical oxidant formation	1.52E-04	9.70E-08	3.73E-06	1.78E-07	0.6%
Water use	2.30E-01	5.85E-13	2.00E-05	1.70E-06	5.3%

After the normalization and weighting of the results of the impact assessment, the impact category related to material resources accounts alone for more than 80% of the total environmental impact of the PV system. It is worth noting that this outcome is influenced by the specific methodological assumptions adopted, especially those concerning normalization and weighting. In order to provide further insights on other impact categories as well, it was decided to take into consideration also water use and climate change.

Impact categories contribution

For each impact category, the contribution of the various processes involved in the life cycle of the photovoltaic system was quantified and examined, with the aim of identifying the most environmentally impactful processes.

Climate change

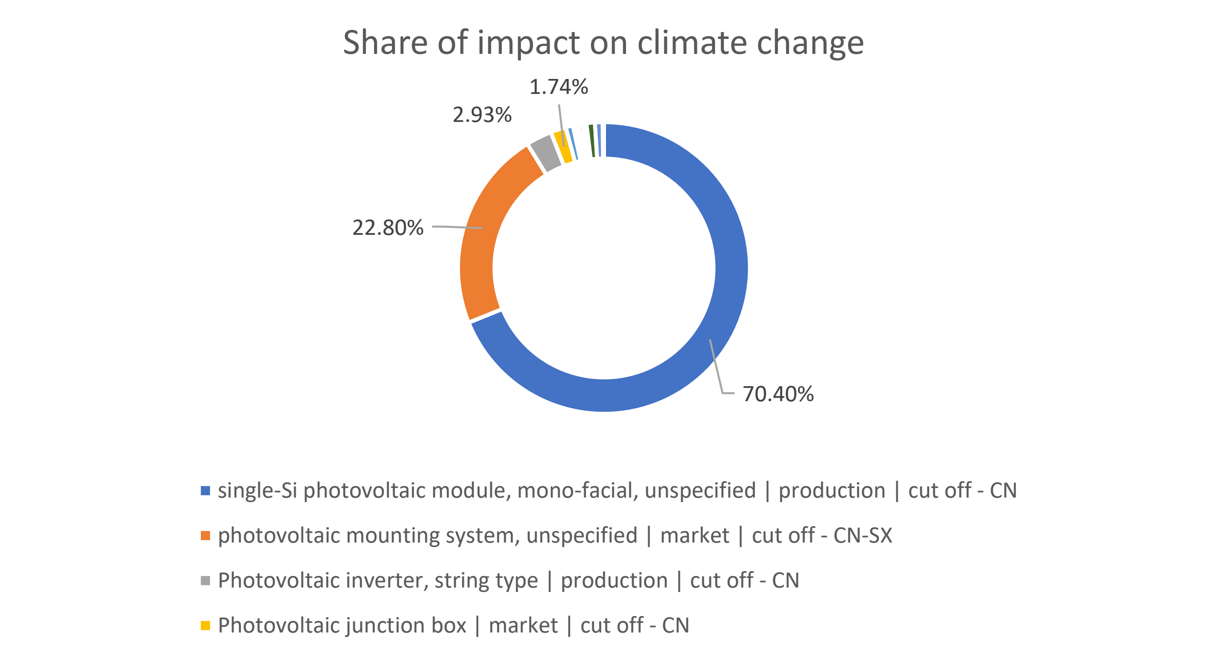


Figure 5- Representation of the share of the processes contributing to climate change

The total impact on climate change is 3.44E-02 kgCO_2eq (±5.78E-13). From figure 5, it is possible to notice how the production of the single-Si photovoltaic module represents the highest contribution to climate change. Unfortunately, as HiQLCD database is characterized by the use of system process, it is not possible to obtain further details on the components or processes behind the production of the module which explain such percentage. Nevertheless, if the corresponding process in ecoinvent database is considered (photovoltaic panel production, single-Si wafer), it is possible to observe that the main impacts on climate change are linked to the materials used for the production of the photovoltaic panel like silicon, steel, electricity used for production etc. Indeed, the mining and processing of PV materials and the manufacturing of the panels are notably processes causing the impact on climate change of PV system to rise, despite the lack of emissions in the use phase.
Similarly, for the mounting system the corresponding ecoinvent process indicates the use of aluminum as the main cause of the impact on climate change.

The remaining components and processes within the life cycle of the photovoltaic system contribute only marginally to the overall impact on climate change. This is primarily due to the fact that the PV module and mounting system constitute the largest share of the system's physical composition.

Material resources

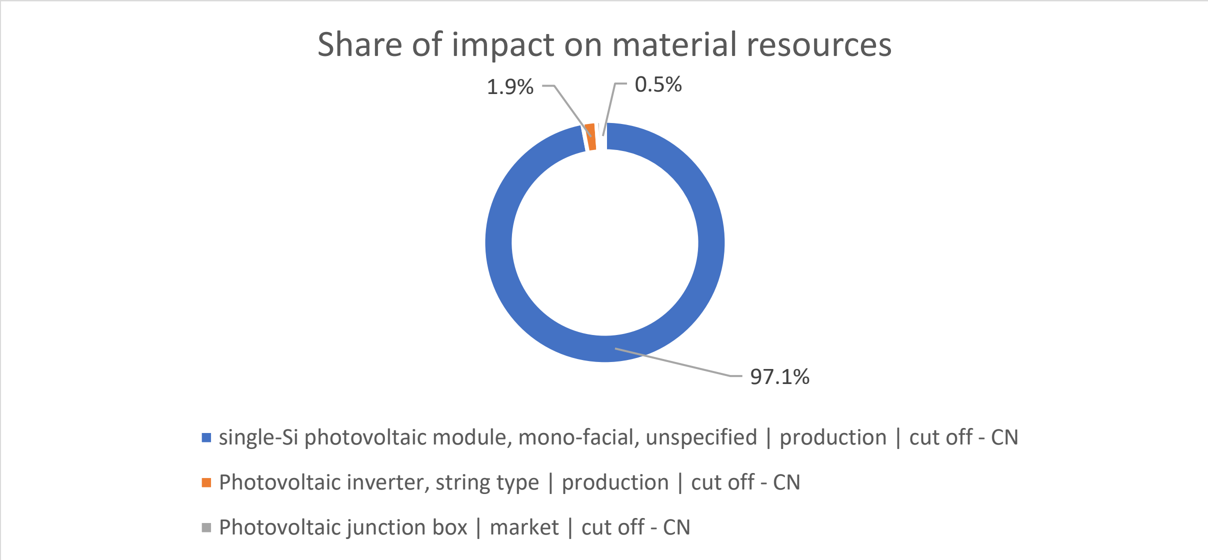


Figure 6- Representation of the share of the processes contributing to material resources depletion

The total impact on material resources is 2.31E-05 kg Sb-Eq (±2.12E-04). In this case, the impact of the photovoltaic module production on the total impact is even more visible than it was with climate change. This is primarily due to the intensive demand for raw materials such as silicon, silver, aluminum, glass and other materials that need to be mined and extracted in order to build a photovoltaic module. Such findings highlight even more the importance of recycling, in order to lower the impact on the depletion of virgin materials such as aluminum, copper etc.

Water use

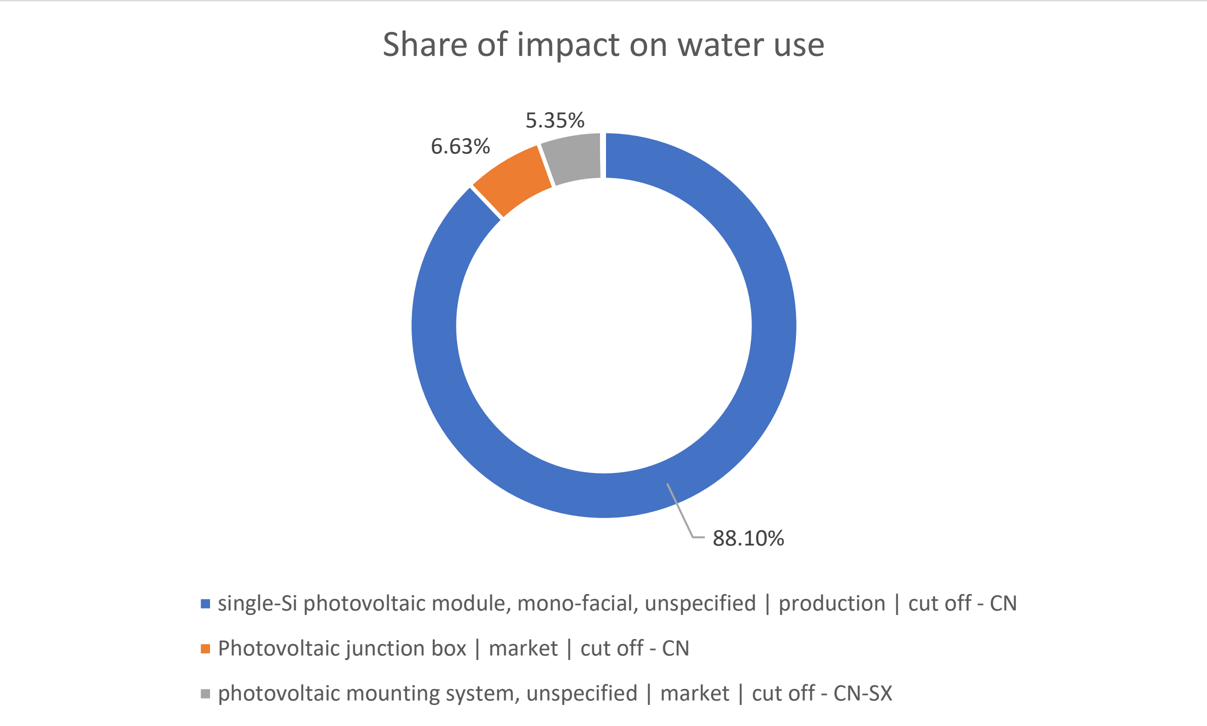


Figure 7- Representation of the share of the processes contributing to water use

The total impact on water use is 2.30E-01 m3 world Eq deprived (±5.85E-13). Again, the biggest contribution is linked to the production of the single-Si photovoltaic module, followed by the junction box production and the photovoltaic mounting system. This is largely due to the energy-intensive manufacturing of silicon wafers and solar cells, which involves multiple chemical treatments and processes requiring water.

IV. Comparison with a model based on ecoinvent only

In this section, a comparative analysis is provided between the model built using HiQLCD in combination with ecoinvent and another model representing the same PV system relying exclusively on ecoinvent. It is important to underline how, in order to model the first phase of the components sourcing with ecoinvent, the supply flows were not regionalized for China; instead, global market processes were adopted, as detailed in Table 13. The input quantities used for this modeling correspond to those outlined in paragraph 1.a, which served as the basis for harmonizing inventory data with the HiQLCD database.

Table 13 - Process representing the sourcing of the components of the photovoltaic system using ecoinvent database

Input			
Flow	Amount	Unit	Provider
inverter, 2.5kW	2.4	Item(s)	market for inverter, 2.5kW | inverter, 2.5kW | Cutoff, U - GLO
photovoltaic mounting system, for slanted-roof installation	21.429	m2	market for photovoltaic mounting system, for slanted-roof installation | photovoltaic mounting system, for slanted-roof installation | Cutoff, U - GLO
photovoltaic panel, single-Si wafer	22.071	m2	market for photovoltaic panel, single-Si wafer | photovoltaic panel, single-Si wafer | Cutoff, U - GLO
photovoltaics, electric installation for 3kWp module, at building	1	Item(s)	market for photovoltaics, electric installation for 3kWp module, at building | photovoltaics, electric installation for 3kWp module, at building | Cutoff, U - GLO
Output			
Flow	Amount	Unit	Provider
PV system components	1	Item(s)	

Once the LCIA was performed, it was possible to observe how when only ecoinvent database is used, the total contribution is more distributed across multiple impact categories (table 14). Therefore, in order to reach the percentage equal to 80% to satisfy the Pareto principle, more impact categories have to be taken into account.

Table 14 - Results of the impact analysis. The values in green are those that satisfied the Pareto rule.

Impact category	Result	Normalized	Weighted	Contribution
Acidification	8.43E-04	1.52E-05	9.41E-07	6.6%
Climate change	1.12E-01	1.49E-05	3.13E-06	22.0%
Ecotoxicity: freshwater	9.98E-01	1.76E-05	3.38E-07	2.4%
Energy resources: non-renewable	1.43E+00	2.20E-05	1.83E-06	12.9%
Eutrophication: freshwater	7.03E-05	4.38E-05	1.23E-06	8.6%
Eutrophication: marine	1.31E-04	6.68E-06	1.98E-07	1.4%

Table 14 - Results of the impact analysis. The values in green are those that satisfied the Pareto rule.

Eutrophication: terrestrial	1.37E-03	7.76E-06	2.88E-07	2.0%
Human toxicity: carcinogenic	5.98E-11	3.46E-06	7.38E-08	0.5%
Human toxicity: non-carcinogenic	4.08E-09	3.17E-05	5.83E-07	4.1%
Ionising radiation: human health	9.72E-03	2.30E-06	1.15E-07	0.8%
Land use	4.41E-01	5.38E-07	4.28E-08	0.3%
Material resources: metals/minerals	2.37E-06	3.73E-05	2.82E-06	19.8%
Ozone depletion	9.34E-09	1.78E-07	1.13E-08	0.1%
Particulate matter formation	7.55E-09	1.27E-05	1.14E-06	8.0%
Photochemical oxidant formation	4.85E-04	1.19E-05	5.67E-07	4.0%
Water use	1.28E-01	1.12E-05	9.51E-07	6.7%

Afterwards, a comparison of the impact assessment results between the two models revealed that the ecoinvent-only model presents higher environmental impacts than the one where HiQLCD was used to model the upstream phase of the life cycle of the PV system (figure 8). Indeed, the only categories showing a higher impact when the life cycle is modeled with the combination of the two databases are material resources and water use. This suggests that HiQLCD places greater emphasis on resource extraction and consumption processes.

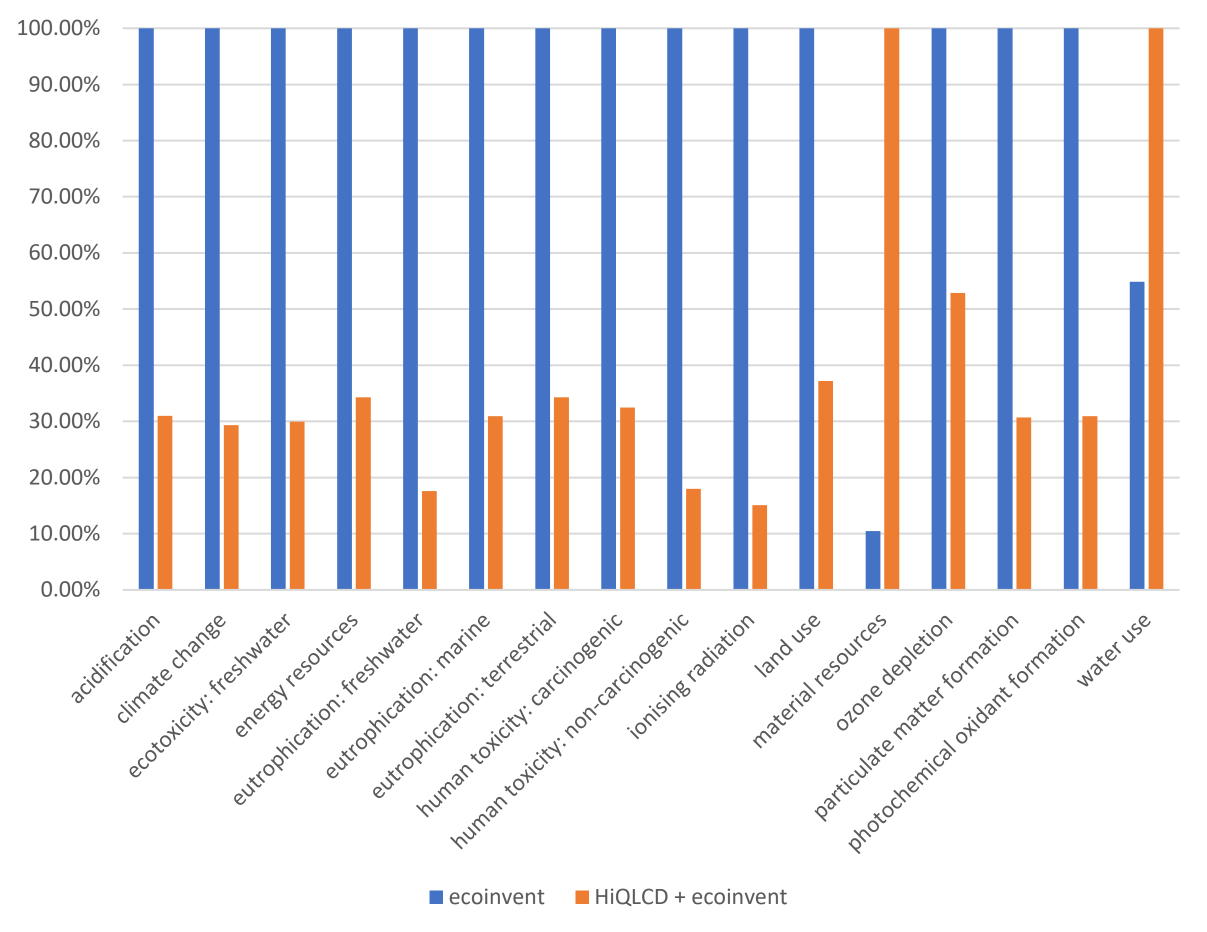
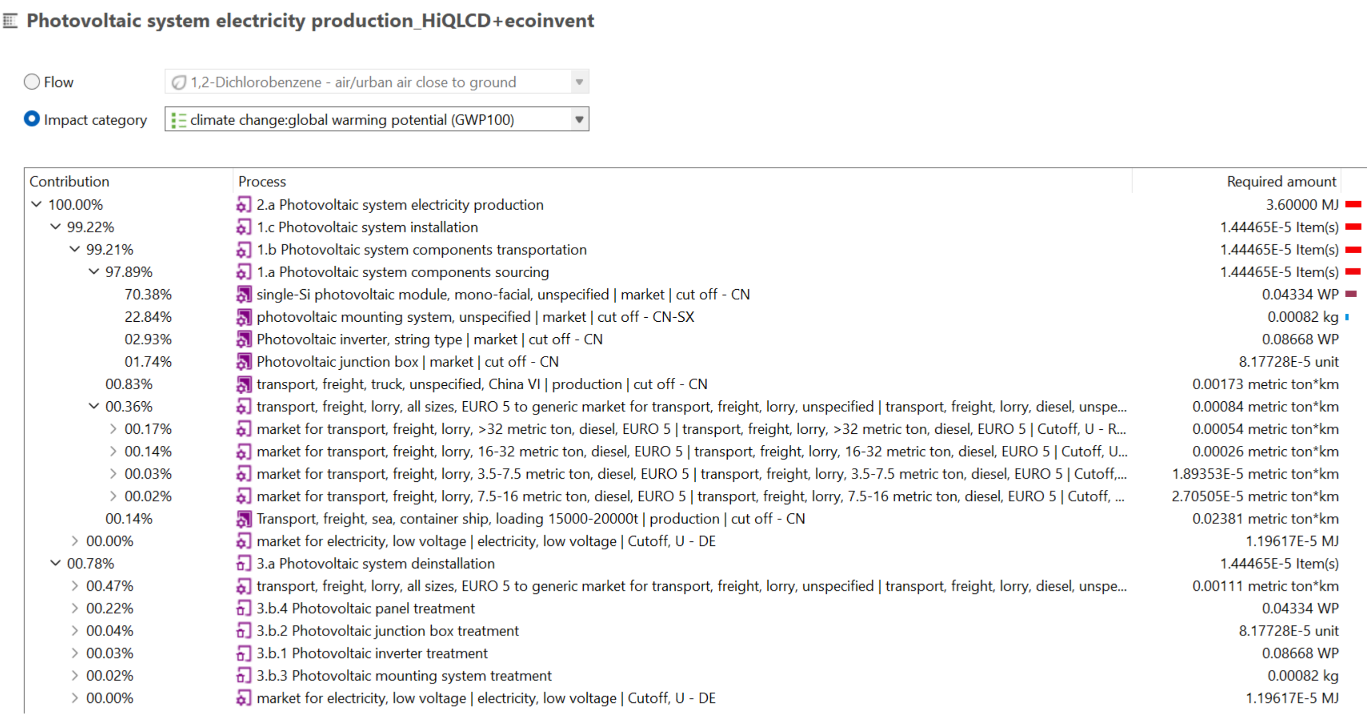


Figure 8 – Comparison of the results of the different impact categories between the model where HiQLCD and ecoinvent were used and the one where ecoinvent only was taken into account.

V. Conclusions

This case study aimed to model the life cycle of a photovoltaic system by combining the recently developed Chinese database HiQLCD for the upstream processes with ecoinvent to represent the use and end-of-life phases. This approach was chosen to improve the geographical accuracy of the life cycle representation, aligning dataset selection with the actual location of each phase. Specifically, using the Chinese database for manufacturing processes provided a more realistic depiction of production conditions in China. Indeed, ecoinvent alone lacks China-specific data. At the same time, ecoinvent proved more suitable for modelling the use and disposal stages, reflecting German or broader European conditions more faithfully than the HiQLCD database, which remains limited to the Chinese context. Therefore, this study supports the idea that integrating multiple databases tailored to regional contexts enhances the credibility and reality of Life Cycle Assessments, offering a more trustworthy portrayal of the product's environmental profile across its entire life span.

Afterwards, the main environmental hotspots within the life cycle of the photovoltaic system were identified. The production of the photovoltaic module emerged as the most impactful phase, in line with findings reported in existing literature and with the fact that energy-intensive processes are involved in wafer and cell manufacturing. It is important to note that, in this study, the end-of-life stage was modeled to include recycling processes, which contributed to a reduction in the environmental burden of this phase compared to scenarios without recycling. Furthermore, the end-of-life phase was simplified with respect to actual conditions, as it considered only the electricity flows while excluding other resource-related inputs. This simplification may have influenced the results and should be taken into account when interpreting the overall life cycle impacts.



Photovoltaic system electricity production_HiQLCD+ecoinvent

Flow: 1,2-Dichlorobenzene - air/urban air close to ground

Impact category: climate change:global warming potential (GWP100)

Contribution	Process	Required amount
100.00%	2.a Photovoltaic system electricity production	3.60000 MJ
99.22%	1.c Photovoltaic system installation	1.44465E-5 Item(s)
99.21%	1.b Photovoltaic system components transportation	1.44465E-5 Item(s)
97.89%	1.a Photovoltaic system components sourcing	1.44465E-5 Item(s)
70.38%	single-Si photovoltaic module, mono-facial, unspecified | market | cut off - CN	0.04334 WP
22.84%	photovoltaic mounting system, unspecified | market | cut off - CN-SX	0.00082 kg
02.93%	Photovoltaic inverter, string type | market | cut off - CN	0.08668 WP
01.74%	Photovoltaic junction box | market | cut off - CN	8.17728E-5 unit
00.83%	transport, freight, truck, unspecified, China VI | production | cut off - CN	0.00173 metric ton*km
00.36%	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspe...	0.00084 metric ton*km
00.17%	market for transport, freight, lorry, >32 metric ton, diesel, EURO 5 | transport, freight, lorry, >32 metric ton, diesel, EURO 5 | Cutoff, U - R...	0.00054 metric ton*km
00.14%	market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 | transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 | Cutoff, U...	0.00026 metric ton*km
00.03%	market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 | transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 | Cutoff,...	1.89353E-5 metric ton*km
00.02%	market for transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 | transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 | Cutoff, ...	2.70505E-5 metric ton*km
00.14%	Transport, freight, sea, container ship, loading 15000-20000t | production | cut off - CN	0.02381 metric ton*km
00.00%	market for electricity, low voltage | electricity, low voltage | Cutoff, U - DE	1.19617E-5 MJ
00.78%	3.a Photovoltaic system deinstallation	1.44465E-5 Item(s)
00.47%	transport, freight, lorry, all sizes, EURO 5 to generic market for transport, freight, lorry, unspecified | transport, freight, lorry, diesel, unspe...	0.00111 metric ton*km
00.22%	3.b.4 Photovoltaic panel treatment	0.04334 WP
00.04%	3.b.2 Photovoltaic junction box treatment	8.17728E-5 unit
00.03%	3.b.1 Photovoltaic inverter treatment	0.08668 WP
00.02%	3.b.3 Photovoltaic mounting system treatment	0.00082 kg
00.00%	market for electricity, low voltage | electricity, low voltage | Cutoff, U - DE	1.19617E-5 MJ

Figure 9 – Contribution tree tab of the LCIA of the photovoltaic system showing the presence of processes from both ecoinvent and HiQLCD database.

Another key takeaway is about the Life Cycle Impact Assessment phase, where it was observed that the HiQLCD database is fully compatible with the LCIA methods available in openLCA. As illustrated in Figure 9, the impact assessment method successfully identified and incorporated processes from both databases into the calculation. The distinction between the two sources is visually evident: processes from the HiQLCD database are system processes, represented by solid rectangles, whereas unit processes from the ecoinvent database are characterized by empty rectangles. This graphical differentiation facilitates the interpretation and confirms the integration of HiQLCD within the openLCA framework. It also leads to another significant difference between the two databases: the HiQLCD database relies on system processes, which integrate entire life cycle stages into aggregated datasets. This means that individual inputs and outputs are not explicitly modeled. In contrast, ecoinvent adopts a unit process approach, where each step of the life cycle is represented separately, allowing for greater flexibility in modifying or analyzing specific flows.

Finally, a comparative analysis was conducted between two LCA models of the same PV system: one built using both the HiQLCD and ecoinvent databases and the other relying on ecoinvent only. The results revealed notable differences in the impact assessment outcomes. Namely, the model incorporating HiQLCD with ecoinvent showed a significantly higher overall impact associated with the "material resources" category, which alone accounted for the majority of the total environmental burden. In contrast, the model based exclusively on ecoinvent presented more evenly distributed impacts across multiple categories. These discrepancies can be attributed to the fact that HiQLCD offers greater regional representativeness in terms of Chinese production and consumption patterns, and provides a more refined modeling of material use and sourcing in the region. In comparison, ecoinvent, while comprehensive, may lack precision in modeling supply chains and extraction of raw materials in China. Therefore, HiQLCD' s emphasis on the environmental implications of raw material use, especially metals and minerals essential to PV technologies, results in a more pronounced impact profile in that category. This suggests that the choice of database in LCA modeling can significantly influence the interpretation of environmental impacts, so it can be concluded that it is important to use regionally and technologically representative datasets to ensure more accurate assessments, whenever possible.

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