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High-resolution and localized parametric embodied impact calculator of PV systems

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Abstract. Buildings are responsible for a large amount of greenhouse gas emissions in the world. In order to decarbonize the electricity grid and reduce the environmental impact of the building stock, photovoltaic panels can be installed. However, in order to assess the environmental impact of PVs, the whole life cycle has to be considered including embodied emissions. Several options for photovoltaics exist on the market or are under development including silicon-based panels, thin films, and third generation panels. Currently, many configurations of the panels exist making it difficult to estimate the embodied impact. The goal of this paper is to close this gap by providing a parametric PV carbon calculator for designers and decision-makers. In this study, the embodied impact of different PV types and configurations is assessed. First, the life cycle inventories data and bill of quantities for different generations' panel types are gathered. Second, life cycle impact assessment is performed. The results of the analysis are presented in a form of a software application allowing users to select the panel's composition, e.g., frame and glass type, cell type, encapsulant, etc. The developed application will assist in understanding the impact of choices made in regards to PV systems and will support engineers and architects in the selection of the photovoltaic panels from embodied impact perspective.

1. Introduction

Buildings are responsible for a large amount of energy and greenhouse gas emissions in the world. According to the Swiss Energy strategy 2050, and a new long-term climate strategy report published by the Federal Council in 2021, the energy consumption of the building sector in Switzerland has to be reduced to 55 TWh [1,2]. Along with the energy reduction, the promotion of renewable sources and the overall net-zero target for all greenhouse gas (GHG) emissions must be achieved [1,2]. One of the possible ways to eliminate fossil fuels, which is most achievable due to the already existing technology, is solar photovoltaics (PVs). PVs are systems that directly produce electricity from sunlight, which is the most abundant energy source on Earth. Potentially, it is possible to cover all the electricity need in the world by the use of solar panels as it was previously shown that about 50% of the total global rooftop area is required to cover the yearly global electricity demand [3]. However, to account for the environmental impact of PVs, the whole life cycle of the system has to be considered from the materials' production to end of life. The embodied emissions of PV panels highly depend on the type of the panel and location of the production [4].

In general, three solar panel generations exist on the market or currently are in development in research. The first generation panels are based on silicon wafers using either mono or poly silicon crystals. This PV type has the highest efficiency with 26.7% and it currently represents 95% of the market [5,6]. While having high efficiency, the first generation panels are also the most carbon intensive in production due to the high energy need for silicon solar grade. The second generation panel type introduced the thin-film panels, which are based on one or more layers of thin film material that absorbs light. Such materials are amorphous silicon thin film, cadmium telluride (CdTe) thin film, gallium arsenide or copper indium gallium selenide (CIGS). Such panels are lightweight and homogenous in color that provides a larger scale of applications compared to the silicon panels. The efficiency for these panels ranges between 21% and 23% [5,6]. It has also been shown that thin film panels have lower environmental impact than conventional mono/poly-crystalline panels [4]. However, the potentially toxic material used for the CdTe panels and the use of scarce materials for CIGS panels is discussed in research [7,8]. The third generation panels are the emerging cell technology that is currently in rapid development and ongoing research projects. Such panels include perovskite, organic and dye-sensitized solar cells. Recent research shows that the highest achieved efficiency for the third generation panels is ranging from 12% to 25% [5]. The third generation panels combine the high efficiency of the conventional silicon cells and thin-film technology from the second generation panels. The overview of the panels is shown in Figure 1.

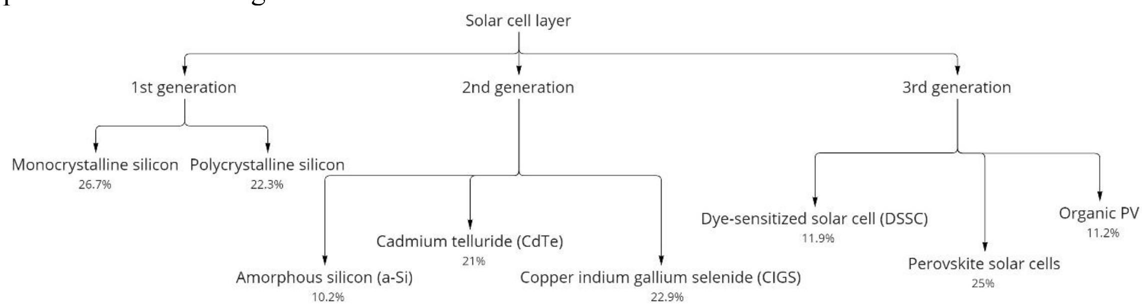

Figure 1. An overview of the panel types

Considering the environmental impact of the panels, the fabrication of the PV panels involves the processing of different materials that might produce various emissions. It has been shown that environmental impact from the panels production is not negligible and has to be considered in life cycle assessment (LCA) [9]. The embodied carbon drastically varies between the different panels generation. The Figure 2 shows the resulting global warming potential (GWP) for the European panels that were available in the Ecoinvent database [10]. Life cycle impact assessment as defined in the IPCC 2013 report and global warming potential (GWP) indicator are taken for the result representation [11].

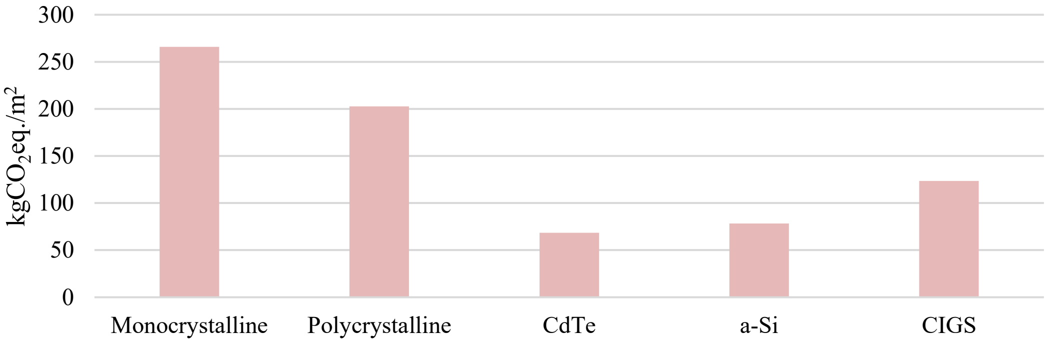

Figure 2. The results of GWP for the available solar panel types in Ecoinvent 3.9

However, the environmental impact of the panel highly depends on the panel composition, which in turn depends on the selected components and associated production location. For instance, the possible glazing options for the panels, selected encapsulant or the aluminum frame presence varies in literature and between the panels' producers. In Figure 3, the possible glass options for CdTe panels with the corresponding environmental impact are shown. The data for the glazing options is taken from Ecoinvent 3.9 and environmental product declarations [10,12]. In Figure 4, the resulting environmental impacts of the CdTe panel considering different types of glass can be seen.

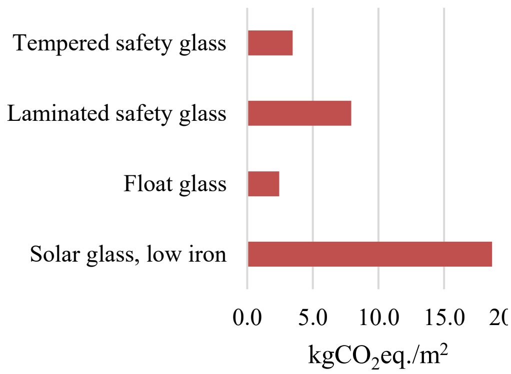

Figure 3. Possible glass options for CdTe panel with the corresponding environmental impact

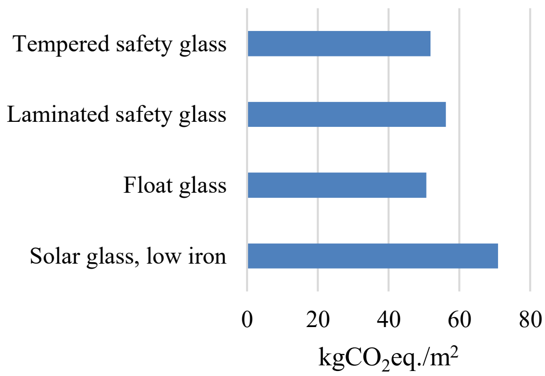

Figure 4. GWP results for CdTe panel considering different glass options

Several papers included embodied analysis of PVs, however, the resulting values are significantly different due to the different locations, components, and databases. The goal of this paper is to provide a parametric embodied carbon calculator for different panel options where the designer has a possibility to select the components within the panel type. Along with the PV panel components' selection it is also possible to select the production origin (i.e. location) of the respective components, as well as balance of the system (BOS), which is a term to describe all components of a PV system other than the panel itself (wiring, mounting system, inverters, batteries, etc).

2. Methodology

The methodology of the paper is shown in Figure 5. First, the database is loaded. Then, the user gets a possibility to select the panel type. Afterwards, the optional choice of the components within the selected panel type can be specified. The choice of the mechanical and electrical balancing of the system can also be optionally selected. The choice of the location for either the whole panel or components parts is then determined and overall impact is achieved. Each step of the process is described in details below.

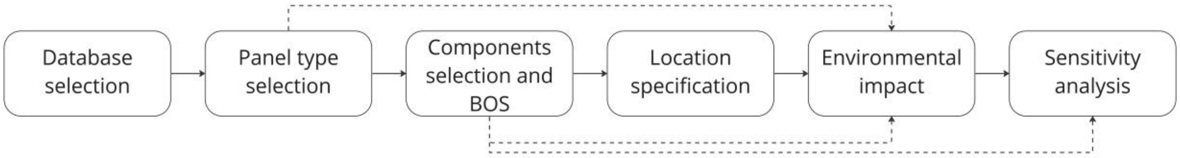

Figure 5. Methodology of the paper

First, the database is loaded. By default, the latest version of Ecoinvent as one of the most consistent and transparent life cycle inventory databases is used [10]. In this study, the selected database is Ecoinvent 3.9. However, the previous versions of Ecoinvent can also be applied. The database is loaded to the Brightway2 software. Brightway2 is an open source framework for life cycle assessment, which is based on python programming language [13]. Brightway2 allows fast dynamic LCA with custom functions and regionalization possibilities as well as global sensitivity analysis [14].

Once the data is loaded, the second step is the selection of the panel type. The following options are possible to select – mono and polycrystalline, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) thin films, perovskite silicon tandem, perovskite as well as organic PV panels. The selection of the panels can be explained by the largest market share or by the fast development in research.

The choice of the panels allows afterwards to get an impact directly or gives a possibility for further specification of the components in step three. Depending on the panel type, different components' options are available. For instance, for the silicon-based panels, the selection of the type of front glass, encapsulant, back sheet are possible. For the thin-film panels, the type of transparent conducting oxide (TCO), metal back contact, front glass, encapsulant and back sheet can be selected. Besides the options for the components, electrical and mechanical BOS can be specified. Within mechanical BOS, the choice of the mounting system can be selected by the material type. Within electrical BOS, the options for wires, inverters, and switches are available. The default parameters are also possible to apply in case of data unavailability.

The fourth step is the location selection. In general, the PV components in Ecoinvent are limited location-wise. An additional study was performed to identify the most influential processes for the PV panel production. The monocrystalline panel from Europe was taken as an example. To identify the influential processes in the panel production, all the processes were tracked down in Simapro software [15]. The results can be seen in the section below.

As an outcome of the embodied impact calculator, the following results can be presented in step five. First, the impacts of the selected panel will be achieved. The Acidification, Climate change, Eutrophication, Depletion of abiotic resources, Ozone depletion, Land use, Eco-toxicity, human toxicity, and Ionizing radiation indicators can be seen as the ones that are recommended to be considered in LCA of PVs [17,18]. Besides the impacts, the contribution analysis in step six with the most influential components in the PV panel will be shown in order to have a possibility to lower down the embodied impact.

3. Results

The results for the influential processes of the monocrystalline wafer production can be seen in Figure 6. It has previously been confirmed that the most impact in the production of Mono/Polycrystalline panel is coming from the wafer production, therefore the results for this component are shown [16]. As it can be seen from the graph, the most influential process in the production of the single Si wafer is the electricity mix. Another process with high contribution is heat. Therefore, one of the solutions to regionalize the process is the adaptation of country-specific electricity mix. In this work, to regionalize the impact of the PV, the electricity mix was adapted based on the Ecoinvent database, which includes the electricity mix of most of the countries in the world.

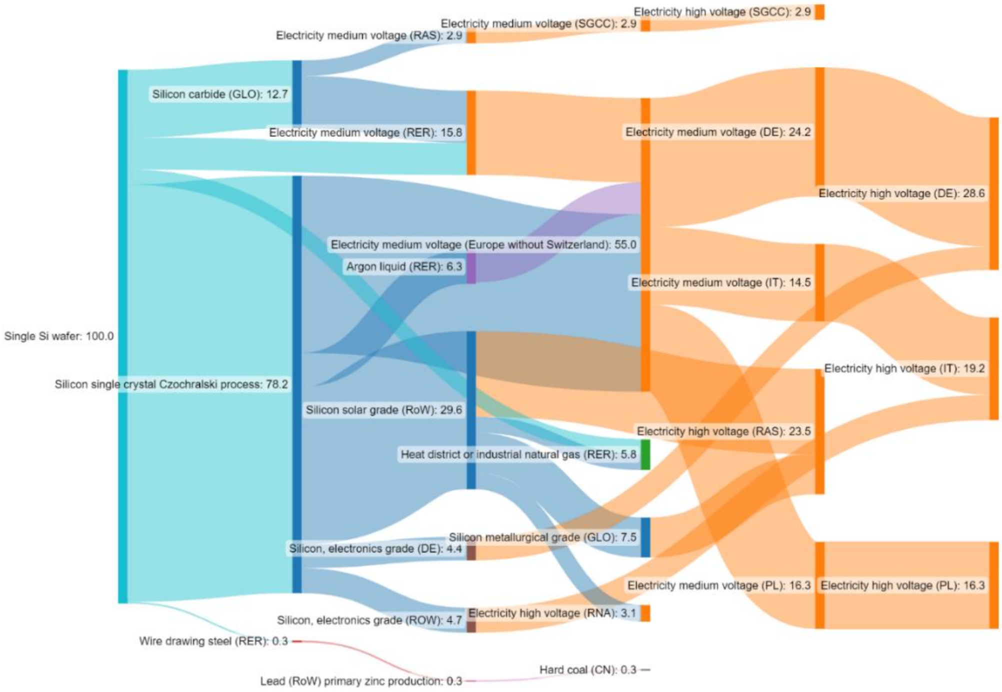

Figure 6. The influential processes in the Single Si wafer production

The resulting workflow of the embodied impact calculator with an exemplary option is shown in Figure 7. When the database is loaded, the type of the panel can be selected. Once the panel is selected and the location of the production is specified, the results of the environmental impact and contribution analysis can be seen directly after specifying the system size. For the further detailed analysis, the components can be selected. For each component, an optional selection of the collation can be defined. In case that the location is not specified, the location for the selected panel type is applied. During the specification of the components, an option of data unavailability (“non-specified”) can be selected. In this case, the default value from the selected panel type in the previous step is taken. Next, BOS can be selected for the specified panel. Balancing can also be applied directly after the panel selection in the first step in case no components’ specification is applied. In the BOS section, the selection of the inverters, wires and mounting system is possible. As in the previous step, the location of the components of the BOS can be specified. Once the system is selected, the system size in either kWp or m^2 can be inserted.

The representation of the results can be seen in Figure 8 and Figure 9. First, the impact for different indicators is shown in a radar chart in relative units and several panels can be compared. In case only

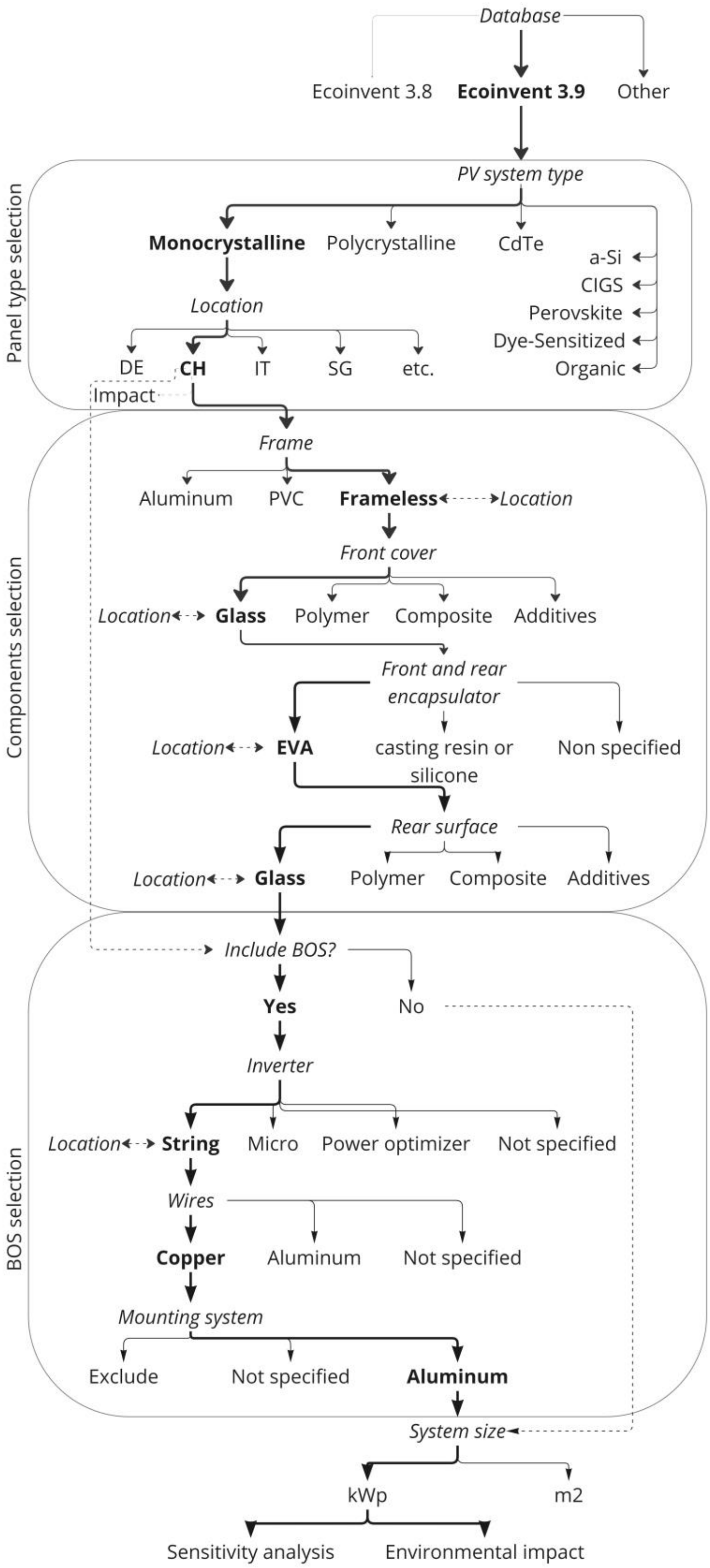

Figure 7. The resulting workflow with an exemplary option (in bold). The selection options are shown in italic font, dashed lines represent the optional selection.

one panel is chosen for the analysis, the results in absolute values in the form of a table can also be seen or can be represented in relative terms in a bar chart. The second visualization graph shows the contribution of the components to the overall impact for the selected panel type.

4. Discussion

Environmental analysis of PV systems is an essential study that assists the choice of PV technology. The choice of PV system is not a trivial task as besides the environmental analysis, PV system should also be efficient, cost-effective, integrated into the design and be accepted by the society. In this work, the focus was on the parametric embodied analysis of the PV systems. Potentially, the analysis can be expanded to account for the solar radiation to electric power conversion efficiency calculation based on the selected components, location-specific cost adaptation and design representation and assistance considering the selected components. Also, adding time resolution into the analysis to account for seasonally varying grid mix from different generation sources and respective grid carbon intensities could be a significant factor in the LCA assessment of PV systems.

Such an analysis will support the designers in the selection of the PV system that is efficient, cost-effective, environmentally-friendly and façade-integrated.

In this work, the selected metric was 1 m^2 or a kWp of the PV panel. In previous research, numerous papers have focused the analysis on the environmental impact of PVs based on the metric of kWh. Such metric might not be sufficient as it can be troublesome to distinguish the embodied impact of the panels as the result is highly affected by the location of the application, which is often different from the PV production country. In this work we aimed to analyse the embodied impact of the specified PV panels, which can be adapted to any location. Therefore, we can link environmental impact of PV systems by the production origin of the respective components.

Several research have analysed the embodied impact of different types of photovoltaics [4,9,19,20]. The results in different research for the same panel type might vary, which occurs due to the different assumptions and allocations, different databases and selected processes. These uncertainties often significantly affect the final result of the impact. The assessment in this paper includes higher precision analysis where the user has an option to select the components of the panel. However, even in higher resolution analysis, uncertainties might affect the resulting impacts. The future potential of this embodied impact calculator is to include simplified uncertainty quantification analysis to show the potential risk of exceeding the estimated impact.

In this work, the location of the components can be adapted through the electricity mix of the country as it was confirmed that the impact of the components to a large extent can be explained by the composition of the country mix. Potentially, this study could be extended to the future projections of the electricity mix and thus, the future PV impact can be assessed.

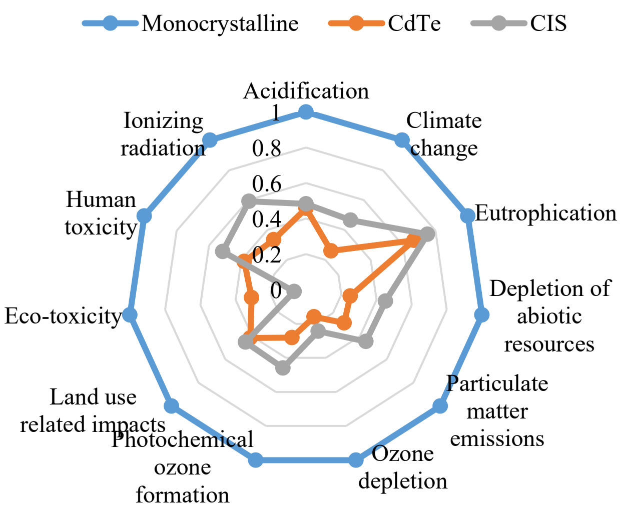

Figure 8. Environmental impacts representation for several panel types

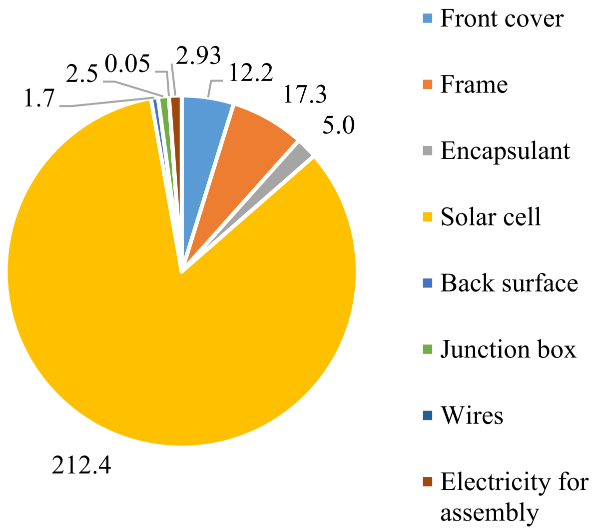

Figure 9. Contribution analysis of the components to the overall impact for the selected panel type

Limitations and further work

In this work, the specification of the components within each panel type is proposed. The selection of the materials for components was selected based on the inventory analyses, research papers, and producers' datasheets. However, some options might not be suitable for the selected panel type. The amount of the materials for each component needed for 1 m^2 of the panel type is also based on various sources and the average value for the quantities is taken. However, in the future, the value for the material quantities will also be an optional parameter.

In this work, the number of possible panel types is explained by the ones that have a high share on the market or are currently being fast developed in research. However, the calculator does not include the producer-specific panel types, which can also be beneficial for the designers. These options will be added in the future.

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5. Conclusion

With the increasing use of PV panels for buildings and the increasing number of panel alternatives, choosing the right panel with a low environmental impact becomes an important task for designers. The environmental impact of the PV panel highly depends on the panel composition, which in turn depends on the selected components and associated production location, making the estimation of the embodied environmental impact complex. To provide guidance for designers, this paper introduces the parametric embodied impact calculator for PV systems. The algorithm allows the designer to select the components within different panel types. The calculator can be adapted to represent different locations using the specific country's electricity mix. The results for relevant indicators for PV systems can be seen along with the contribution analysis of the components. This provides designers such as architects or engineers a sound basis for decision-making when selecting a PV system for their building. Furthermore, from the results we can recognize significant variation in environmental impact based on the location to which the analysis is applied to, mainly due to the differences in local electricity mix and grid carbon intensities involved in the production process of the respective components. In future studies, the additional analysis of efficiency, costs and design can be added to support the designers in the selection of the optimal PV panel type for different locations. In conclusion, our parametric PV tool allows for a higher-resolution and precise assessment of a systems' impact, enabling planners, designers and engineers to identify highest potentials to improve overall environmental performance.

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