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High-resolution parametric embodied impact configurator for PV and BIPV systems

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ABSTRACT

To fully analyze the potential of PVs in achieving sustainable energy goals, careful consideration of the life cycle including the embodied impact is needed. Despite the existence of various life cycle inventories for PV modules, there remains a lack of structured and detailed data to enable easy comparison across different technology configurations. Such data is crucial for identifying the components with the highest environmental impact and further optimization. This data gap is an obstacle to informed decision-making processes when evaluating PV designs. The goal of this study is to develop a harmonized, modular database that captures the environmental impact of various PV systems in high resolution. It includes the selection of cell technology, electrical components, frame materials, and the location of production. The environmental assessment includes 14 impact categories. Additionally, a web-based configurator is available, allowing users to quickly estimate the environmental impact of custom PV panels. Through exhaustive sampling of different configurations, the study demonstrates that the Global Warming Potential of a PV panel can range from 10 to 380 $kgCO_2eq/sqm$. The results of this study can support architects, engineers, and planners in estimating the embodied impact of the PV systems, leading to more informed and environmentally conscious design decisions.

1. Introduction

Addressing the high energy consumption of buildings and finding a clean source of energy are important steps in promoting sustainability and reducing environmental impacts. Transitioning to renewable energy sources can play a significant role in achieving these goals. Solar energy is one of the most viable and promising sources of renewable energy. Solar photovoltaics (PV) convert sunlight into energy. The application of PV has grown substantially over the world in recent years. In 2022, the growth rate of PV installation achieved 20 % with a cumulative capacity of 1185 GW [1]. This expansion is driven by multiple factors such as decreasing costs of PV systems, incentives for PV installation, changing policies for feed-in tariffs, and in general, growing environmental awareness [2]. Besides that, the options for PV panel types continue to expand, increasing the efficiency of the panels while also offering various design possibilities. However, it is estimated that a continuous annual growth of 25 % is needed to achieve the target of net zero emissions by 2050 [3].

PV technology has a crucial role in the reduction of the environmental impact and addressing climate change. However, the production of PV modules is related to environmental impacts such as greenhouse gas (GHG) emissions, acidification, eutrophication, and many others. To comprehensively assess the environmental impact of PVs, it is important to consider the whole life cycle from the production of the panel to the operation, replacement, and end-of-life. Life cycle assessment (LCA) can be utilized for that. LCA is a widely adopted methodology for assessing the environmental impact of a product over its life cycle. Several studies have assessed the environmental impact of various PV technologies [4–6]. Furthermore, studies have compared the environmental impact of different PV types [7,8]. It has been shown that first-generation panels such as mono/polycrystalline type have higher embodied carbon than the second-generation thin films due to the carbon-intensive process of silicon production [9]. Embodied carbon is associated with the product stage of the building defined by EN 15978, which refers to the carbon emissions of the raw material supply, transport, and manufacturing of the product [43]. This stage encompasses all processes involved in producing building materials before their use in construction. Embodied carbon is typically measured in $kgCO_2eq$. Recent advancements in research also led to the development of organic PV types that demonstrate considerably lower environmental impact due to the use of organic materials such as polymers as active layers [4,10]. The organic materials used in such PV panels can often be separated using

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low-energy processes at room temperature and recycled. Nevertheless, it has also been shown that such panels are less efficient, and low in stability compared to the inorganic photovoltaic cells [11].

1.1. Embodied impact indicators of PV

Within the environmental indicators, often only Global Warming Potential (GWP), based on Intergovernmental Panel on Climate Change (IPCC) characterization factors, is used as an indicator of climate change [12]. However, it has been shown that photovoltaics might contribute to heavy metal pollution and ecotoxicity (V. M [13]). To comprehensively assess the full life cycle and avoid burden shifting between impact categories, a broader range of impacts must be included and the analysis of relevant life cycle impact categories for photovoltaics needs to be performed. Fthenakis et al [14] and the European Commission [15] have defined 14 environmental indicators to capture a more holistic perspective than focusing on CO_2 emissions only. These include Terrestrial acidification, Climate change, Ozone depletion, Human toxicity carcinogenic and non-carcinogenic, Primary energy fossil, Land use, Photochemical oxidant formation human health and terrestrial ecosystems, Freshwater ecotoxicity, Particulate matter formation, Freshwater eutrophication, Marine eutrophication, Ionizing radiation (European commission, 2019; V [14]).

When assessing the environmental impact of photovoltaics, kilowatt-hour (kWh) is commonly used [16,17]. Using kWh as a functional unit in the context of PV enables the evaluation of the amount of environmental impact associated with the production of each kilowatt-hour of electricity generated by the PV system and considers all the life cycle stages of PV technology. Such an indicator is convenient as it allows a direct comparison of the environmental impact of different technologies with the electricity mix of the region. However, such metrics do not distinguish different life cycle stages as it highly depends on the solar irradiation in the selected location, orientation, and inclination of the panel. Considering the architectural, engineering, and construction (AEC) practice, the most often applied metric for measuring and quantifying various aspects of a building is the surface area measured in square meters (m^2) [18]. This metric is relevant for the assessment of solar energy generation potential, space planning, zoning regulations, material calculations, and various design considerations. Moreover, given the limited remaining carbon budget to achieve the global 2 °C target, the embodied impact should be thoroughly examined to allocate the associated budget [19]. Distinguishing the embodied impact also allows decision-makers to prioritize actions and investments to maximize resource efficiency and minimize environmental impacts.

1.2. Data availability for PV

Despite being one of the most widely applied renewable energy technologies in the market, data on the environmental impacts of PV systems can vary across different sources and lack a comprehensive structure. This variability in data and lack of standardization pose challenges in accurately assessing and comparing the environmental performance of PV systems, especially for practitioners in the AEC sector. There are various reasons associated with this variability. The first one is that the data availability, sources, and quality directly influence the accuracy and reliability of the environmental impact assessment. There are several open-source datasets available for life cycle inventories of PV systems [20,21]. However, often datasets are only available for a specific location and contain different levels of details. Some datasets offer more granular information on the unit processes while others provide only aggregated data. Another reason for data variability is the methodological differences, for instance, life cycle impact assessment (LCIA) methods. Different LCIA methods can employ varying assumptions for characterization factors, which can significantly influence the results. In addition, comparing the results of LCA of PV systems can be challenging due to varying system boundaries. For example, balance of the system (BOS), which generally includes wiring, mounting system, and inverter is often neglected. However, it has been shown that it might significantly influence embodied emissions [22].

1.3. Categorization of PV modules

Another important aspect is the panels' configuration. The composition of the panels frequently varies and depends on the production and manufacturing location as well as the specific technology used. Previous studies have indicated that the GHG emissions associated with the production of PV modules in China are nearly twice as high as those produced in Europe [23]. Therefore, structured data with consistent levels of detail includes information from various locations and covers a range of panel compositions. A recent study demonstrated that the difference between several PV modules with different configurations can be significant [8]. Recent research has also shown that PV panels contribute 2–14 % of the remaining carbon budget required to achieve decarbonization targets [24]. Therefore, a more in-depth and detailed analysis of the embodied impact of PVs is required to reduce PVs' share of the carbon budget and advance progress toward decarbonization goals.

PV modules can be categorized based on their physical characteristics and design. A common physical distinction is made between rigid (glass-glass, glass-foil), flexible, and bi-facial PV (see Fig. 1a). The most common and traditional system type is rigid. Typically, these panels are made of a crystalline solar cell that is encapsulated between the front cover glass and the back sheet. However, glass-glass systems where the back surface also consists of a transparent glazed surface can increase durability and as a result, decrease the degradation rate. Such rigid PV systems can be mounted on fixed structures such as rooftops, ground-mounted systems, or integrated into the façade of a building (i.e. building-integrated photovoltaics).

Flexible thin films are another panel system type. Such panels are made of a thin layer of photovoltaic cells deposited on flexible substrates. Due to the flexibility of such panels, they can be utilized in various applications such as vehicles and irregularly shaped structures. It has been shown that flexible PV panels can be applied to wearable devices [25].

Another type of PV system is bi-facial PV, which recently gained popularity due to its ability to absorb reflected and diffuse light. Bi-facial PVs are constructed with a transparent glass or back sheet on the rare side and are designed to capture sunlight from both sides. Such panels can provide increased energy generation, especially in areas with highly reflected surfaces such as snow, water, or light-colored ground.

Another way to represent the types of PV modules is by generation, each representing a different stage in technology evolution (see Fig. 1 (b)). The efficiencies are represented using the data for the record research cell efficiencies [26]. The first generation is dominated by crystalline silicon modules, which are known as highly efficient and durable. The second generation is characterized by thin films that are made by depositing one or more thin layers of photovoltaic material on a substrate. These module types are characterized by lower efficiency rates compared to crystalline silicon but offer advantages in terms of production cost, flexibility, and performance in low-light conditions. The third generation includes a variety of advanced thin films, which offer promising features such as potential for transparency, flexibility, and roll-to-roll production.

The selection of a suitable panel type depends on several factors such as installation site, available space, and environmental conditions. Each configuration of photovoltaics has a varying environmental impact due to differences in materials, manufacturing processes, and energy generation capabilities.

1.4. Panel manufacturing process

The manufacturing process of PV panels involves several stages from

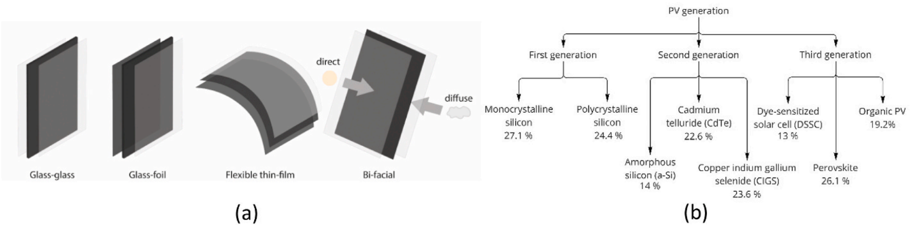


Fig. 1. Categorization of PV systems. a) Panels system type based on physical characteristics. b) Based on cell technology/material.

raw material preparation to panel assembly. The manufacturing process is shown in Fig. 2. The first step in the production process is silicon production, for which a suitable material needs to be selected. Typically, metallurgical-grade silicon is used, which is derived from silica-rich materials like quartz or sand through a reduction process using carbon and heat [27].

Once the silicon is produced, the next step is ingot formation, which serves as the starting material for creating solar cells. Monocrystalline silicon ingots are generally grown using the Czochralski method, in which a seed crystal is dipped into molten silicon and pulled up to obtain a single crystal. Polycrystalline silicon ingots are produced through a chemical vapor deposition (CVD) process, where trichlorosilane gas is decomposed, and silicon is deposited on seed particles [28]. The grown ingots are then sliced into thin wafers using wire saws or other cutting methods.

To produce a solar cell, the wafer then needs to be textured and covered with an anti-reflective coating to reduce reflection and increase light absorption. Metal contacts are then screen-printed onto the wafer to make electrical connections. To assemble a panel, the cells are encapsulated to protect them from environmental factors. Afterward, a back sheet and front glass cover are attached to provide insulation and additional protection. The junction box is fixed to the back surface and contains diodes and wires. Additionally, a frame is attached to provide further support. Furthermore, depending on the installation site, a mounting system is installed to provide the necessary elevation, support, and orientation for optimal sunlight exposure [44].

1.5. *Paper contribution and overview*

As an answer to the lack of comprehensive, harmonized, and modular data on the environmental impact of different PV systems, we aim to present a high-resolution parametric embodied impact database. Furthermore, we develop a configurator that enables a comprehensive evaluation of different PV technologies, while also providing the option to specify the production location. The database on the component level includes the most applied PV technologies with the possibility to specify the material and production location for each component within the panel. The configurator on the module level enables both researchers and practitioners to easily evaluate the environmental impacts of different PV systems' assemblies in different contexts.

In the following, we present our approach to compiling PV data into one comprehensive framework. Besides the collection and merging of databases, we also developed a web-based tool that allows parametric configuration of various PV designs. In the results section, we describe the application of this tool for an exhaustive sampling over the entire database to demonstrate the large range of possible designs and how it influences the systems' embodied impact, including GWP.

2. Methodology

The methodology consists of two parts – the development of a database on the component level and a configurator on the panel level (see Fig. 3). First, the database development is shown and then the configurator development using the database is explained. The data is collected considering the available materials and bill of quantities. Components include the front cover, frame, encapsulant, solar cell, back surface, mounting system, junction box, inverter, and wiring. For each component, the plausible materials and available production locations are included. For instance, for the front cover of the PV panel, there are three available materials: glass, polyethylene terephthalate (PET), and polycarbonate (PC). Each material has distinct properties that can influence the overall performance and environmental impact of the PV panel. Then, the environmental impacts are calculated based on the impact categories relevant to PV analysis and stored in a database for further analysis. In the second part of the methodology, the focus shifts to the impact analysis of PV panels configured using the database, which is utilized as a resource for evaluating the environmental impact of those technologies. For the configurator, a parametric embodied impact calculator that allows for detailed assessment and comparison of different types of PV panels and compositions was developed. It enables users to specify the production location and obtain comprehensive information on the embodied environmental impacts of the selected PV configurations. The details of the methodology are explained below.

2.1. *Component level database*

The panel types represented in the database are Monocrystalline, Polycrystalline, CdTe, CIGS, Perovskite tandem, and Organic PV (OPV). The bill of quantities involved collecting data from various sources, including databases such as Ecoinvent, Environmental Product Declarations (EPD), and relevant research papers. These sources provided information on possible panel compositions and the materials that are available for use. Along with the available materials for the panel composition, the data regarding the amounts of materials per 1 m^2 of the panel is collected. Available production locations are also analyzed according to the data availability. The data is further summarized and matched with the available material in Ecoinvent 3.9, which was used due to its reliability as a consistent and transparent life cycle inventory database [29].

After identifying the materials for PV components from the Ecoinvent database, a life cycle impact assessment (LCIA) is conducted. LCIA quantifies the potential environmental impacts in each impact category by applying characterization factors to the inventory data. LCIA is performed using Brightway - an open-source software package designed for an environmental impact analysis [30]. It provides a framework and

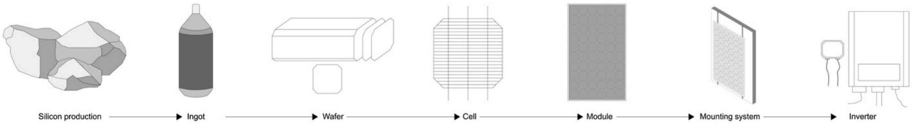


Fig. 2. Panel manufacturing process.

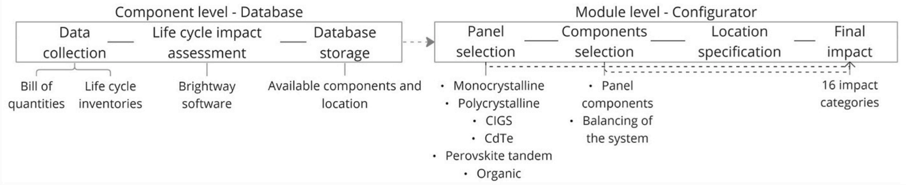


Fig. 3. Methodology.

tools for creating and managing LCA databases, conducting LCIAs, and analyzing the environmental performance of products and systems. During the analysis, 14 impact categories are assessed, following the methodology guidelines of the European Commission and the International Energy Agency (IEA) (European commission, 2019; V [14]). The following impact categories are included – Terrestrial acidification, Climate change, Ozone depletion, Human toxicity carcinogenic and non-carcinogenic, Primary energy fossil, Land use, Photochemical oxidant formation human health and terrestrial ecosystems, Freshwater ecotoxicity, Particulate matter formation, Freshwater eutrophication, Marine eutrophication, Ionizing radiation. The LCIA methodologies ReCiPe 2016 and Cumulative Energy Demand (CED) for the primary energy fossil are applied.

Once the data for environmental impact categories is obtained, the results are stored in JSON format. This format provides compatibility and flexibility for data utilization and integration into various applications and systems. The structure of the database follows the typical structure and components explained in Section 1.4. An example of the structure of a Monocrystalline panel is presented in Fig. 4.

2.2. *Panel level configurator*

The developed configurator requires user input on the selection of the components within the panel type and location for the component. The configurator incorporates several levels of nesting, which require detailed specifications from the user (see Fig. 5). At the first level of the configurator (step 1), the user is provided with options to select the cell type for the panel from the available choices in the database. Once the cell type is established, the user must select which option for each of the components they would like to apply (step 2). Besides the panel composition selection, the balance of the system (BOS) can also be chosen. Within BOS, such components as inverter type, mounting system, and wiring can be selected. In addition to selecting the components, the tool provides the option to choose the electricity mix for the panel assembly through the location specification (step 3). By specifying the electricity mix, it becomes possible to account for panel production in the available country or region. The database includes six possible locations for the electricity generation profiles according to the PV manufacturing capacity [31]. Those are China, Europe, Asia Pacific, North America, India, and Rest of the world (RoW).

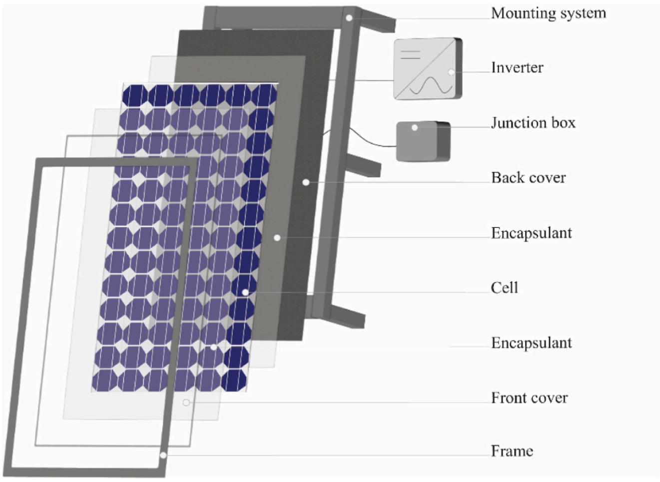


Fig. 4. The monocrystalline panel dissected into individual components or layers that are accessible within the database.

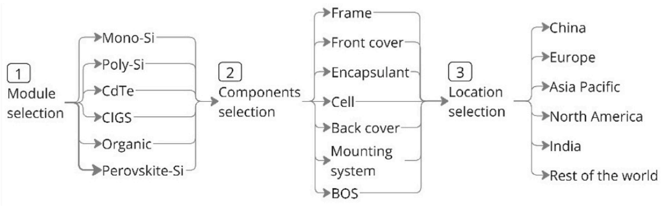


Fig. 5. Specifications required by the user.

The components are chosen in a sequential order, following the layering structure of a panel. An illustrative example of a monocrystalline panel is depicted in Fig. 6. For each group of components, it is possible to specify the materials that are accessible within the database. For instance, for the front cover of the panel several options are available: PET, polycarbonate, and solar glass. These material options reflect the variations commonly used in the industry. Within each component, several locations are available for specification. This allows for the consideration of different manufacturers for the components within the panel. Once the location is specified, the impact is added to the overall environmental impact of the system. In case the material or location is not known, it is possible to select a default value that corresponds to the most frequently employed option.

Once all the materials are selected, the resulting values for various environmental indicators are presented. The functional unit is 1 m^2 of the panel. Pie charts visually depict the entirety of environmental impacts for each of the impact categories, broken down by the panel and BOS components selected.

The final piece of information displayed is a curve and range that describes the potential of the panel in terms of a key impact category, climate change, through emissions impact intensity ($kgCO_2eq./kWh$), for which the equations are shown in Eqs. (1)–(6). For the configured panel we calculate potential annual power production using the PVWatts method [32] for a range (0–1000) of annual irradiance values (kWh/m^2 per annum) and a performance ratio ranging from 0.05 to 1.00 that is controllable by the configurator user. Performance ratio is a simplification of loss within a PV system and the capability of the system to utilise the generated electricity. For each point in this range of annual potential power production we then calculate the possible emissions abated over the lifetime of the panel given a self-consumption factor ranging from 0.05 to 1.00 that is controllable by the configurator user. Self consumption is the ratio of how much generated electricity was consumed in real time to the total amount of generated electricity. It is offered as a choice in the calculation because some carbon accounting methodologies only allow for abated electricity consumption on site to be counted [33]. This then allows the direct comparison of the panel to emissions intensity factors of electricity grids. Lastly, the user can specify the level of emission intensity of the grid and see what level of

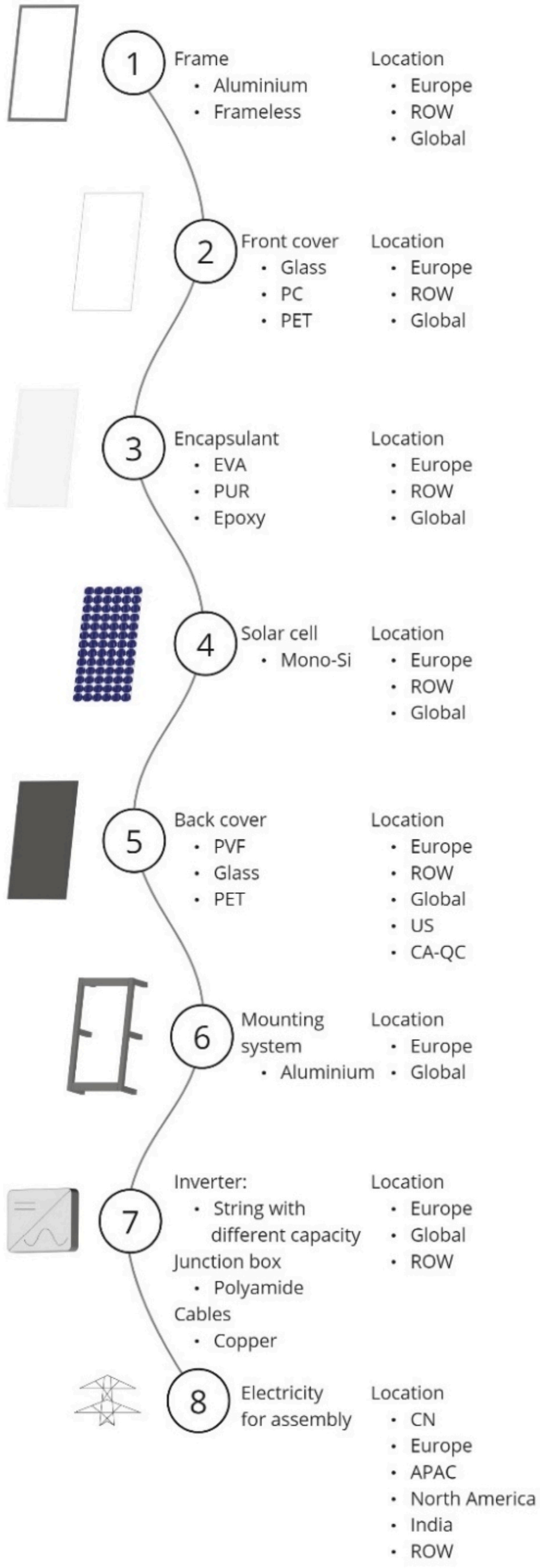


Fig. 6. Components' process selection based on an example of Mono-Si panel.

annual irradiance would be necessary for their configured panel to outperform the grid in terms of lifetime $kgCO_2eq./kWh$.

In the following equations, the calculation method for the emissions intensity of a PV system is described.

$$I_{sys} = \frac{E_{sys}}{P_{sys} * SC} \tag{1}$$

where I_{sys} is the CO_2 intensity of the electricity generated by the system over its lifetime ($kgCO_2eq./kWh$), E_{sys} is the embodied carbon of the system ($kgCO_2eq.$), P_{sys} is the lifetime power generation of the system (kWh), SC is the self consumption ratio of the system (−).

$$E_{sys} = E_{mod} * N_{mod} * A_{mod} \tag{2}$$

where E_{mod} is the embodied carbon of a single module ($kgCO_2eq./m^2$), N_{mod} is the number of modules in the system (#), A_{mod} is the area of a single module (m^2).

$$P_{sys} = P_{mod} * N_{mod} * L_{mod} \tag{3}$$

where P_{mod} is the power generated by one module in a year (kWh/year) using the PVWatts method [32], L_{mod} is the lifetime of the module (years),

$$N_{mod} = \sum_{t=1}^{8760} P_{mod,t} \tag{4}$$

$$P_{mod,t} = \frac{0.008 \cdot G_{eff,t}}{G_{ref}} * P_{ref} * \left(1 + \gamma * \left(T_{mod,t} + T_{ref}\right)\right) \tag{5}$$

where $G_{eff,t}$ is the effective irradiance on the module for the time step t (W/m^2), G_{ref} is the effective irradiance under reference conditions (W/m^2), P_{ref} is the module power output under reference conditions (W), γ is the temperature loss coefficient (-%/°C), $T_{mod,t}$ is the temperature of the module for timestep t (°C), which we calculate using the Ross method [34], T_{ref} is the temperature of the module under reference conditions (°C).

$$T_{mod,t} = T_{air,t} + \frac{T_{NOCT} - 20}{80} * \left(G_{eff} * 0.1\right) \tag{6}$$

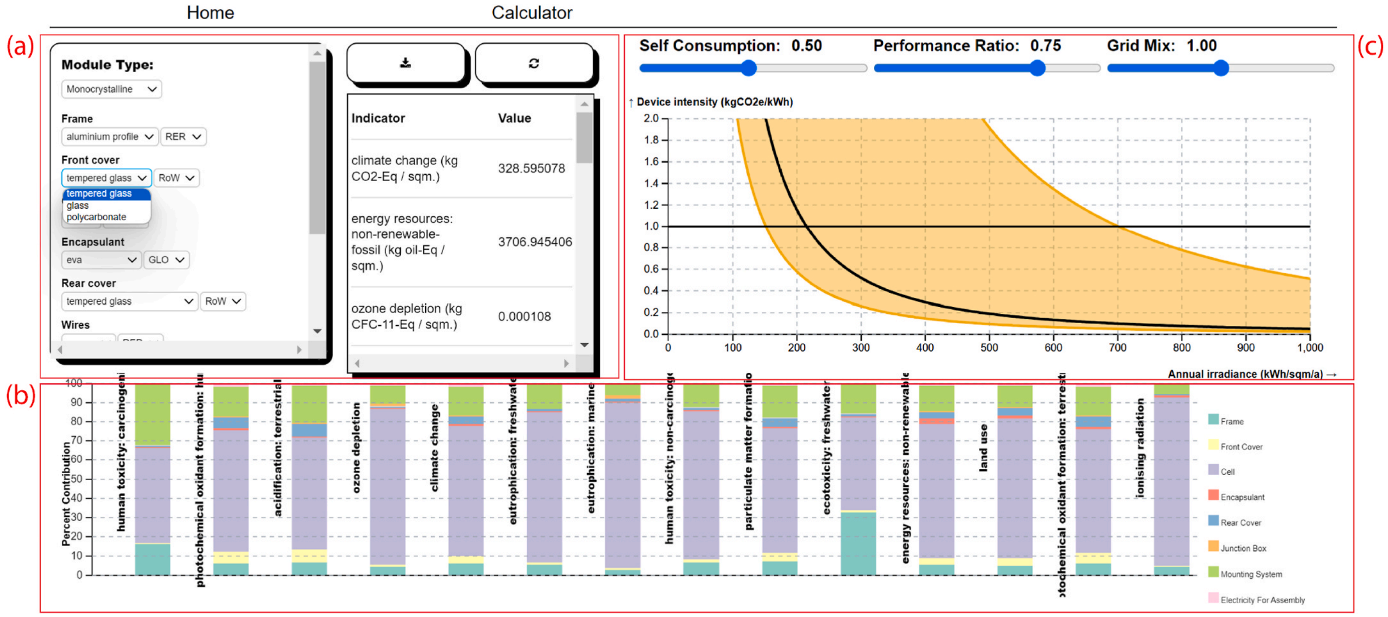
where $T_{air,t}$ is the ambient air temperature at timestep t (°C), T_{NOCT} is the nominal operating cell temperature of the module (°C).

The results also allow for a quick assessment of the major contributors to the environmental impact of the panel. After analyzing the contribution of each component depicted in the pie chart, it becomes feasible to subsequently choose an alternative solution, if one is available, to reduce the embodied environmental impact.

3. Results

This study presents two key outcomes. Firstly, a detailed database evaluating current PV technologies, offering granular insights into system components and production locations. Secondly, a web-based configurator that streamlines the analysis of PV panel embodied impacts, visually represented through stacked bar charts, a 3D model, and the panel carbon curve (Fig. 7). The range of potential solutions available from the various configurator inputs for panel construction is also shown.

The configurator allows users to get a straightforward estimation of the environmental impact associated with the production of the PV panel. The representation of the results in Fig. 6 is divided into 3 parts of module type and component selection (Fig. 6a), impacts of different environmental categories (Fig. 6b), and a ratio of annual solar irradiance and emissions depending on the amount of electricity used for self consumption (Fig. 6c). The module type selection allows for an optional selection of the components within the module as well as the electricity



Module Type: Monocrystalline

Frame: aluminium profile, RER

Front cover: tempered glass, RoW

Encapsulant: eva, GLO

Rear cover: tempered glass, RoW

Indicator	Value
climate change (kg CO2-Eq / sqm.)	328.595078
energy resources: non-renewable-fossil (kg oil-Eq / sqm.)	3706.945406
ozone depletion (kg CFC-11-Eq / sqm.)	0.000108

Self Consumption: 0.50 Performance Ratio: 0.75 Grid Mix: 1.00

Fig. 7. The configurator is a lightweight web application for building a generic PV module and analyzing its impact indicators, available at https://acacia.arch.ethz.ch/calculator.

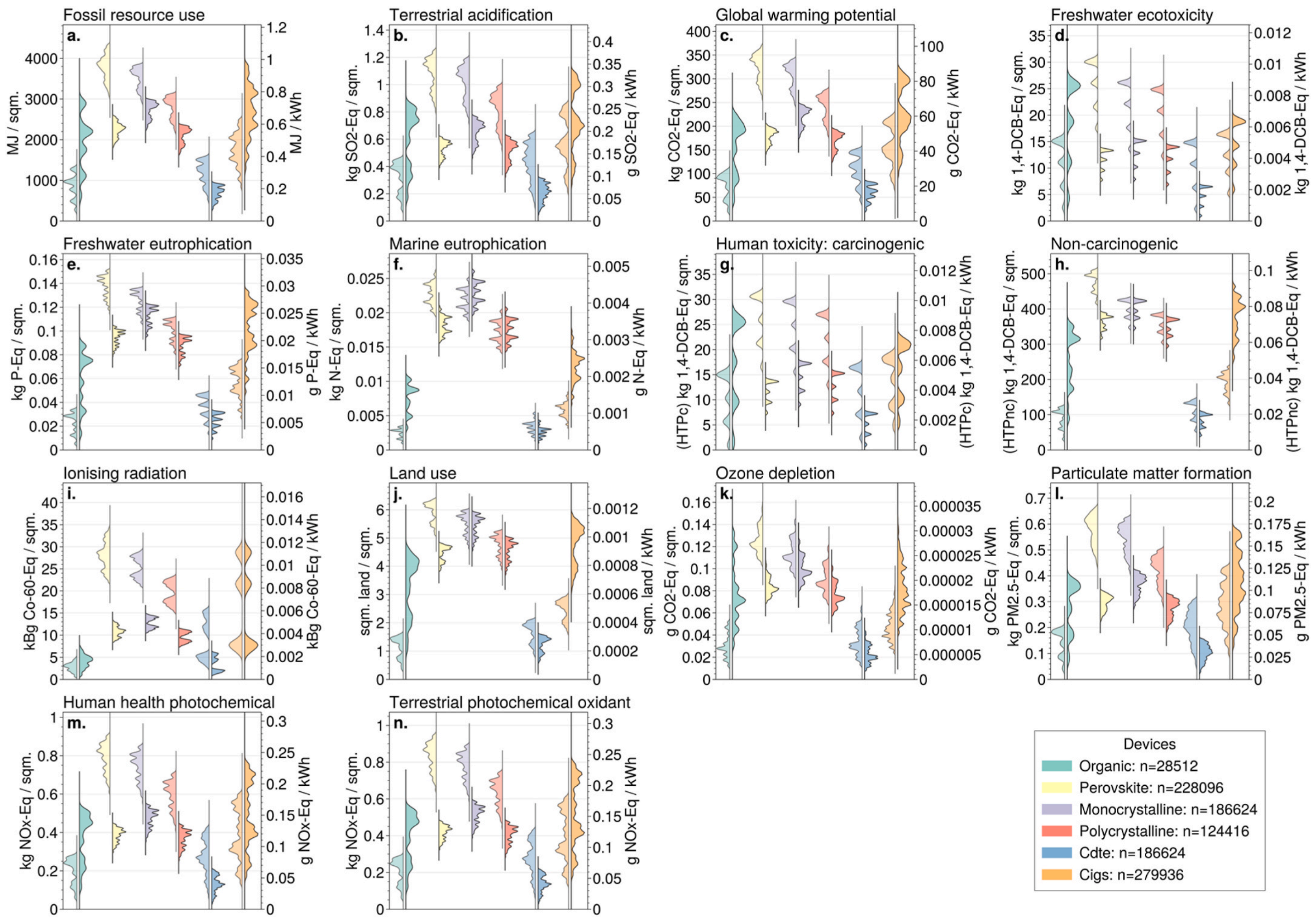


Fig. 8. Environmental impact of the most common PV Module combinations across multiple categories. The indicator score was calculated for every unique possible combination within the configurator's layer and location options for each module where n is the total count for each module type.

mix at the point of assembly. Besides selecting the materials, specifications for the location are also available. The results are available in absolute values and in percentages to evaluate the component with the highest contribution. Besides only looking at the GHG emissions, the configurator directs focus to other relevant impact categories, broadening the scope of environmental assessment. The results are updated in real time once another component is selected. The results of the embodied impact are coupled with the environmental impact measured in $kgCO_2eq./kWh$ and the curve is updated automatically depending on the share of electricity used for self consumption and performance ratio. The grid emissions can also be selected to be able to see the annual irradiance needed to have a system perform as well or better than the specified electricity mix.

The developed database and configurator can be used autonomously but can also be coupled further to optimization workflows, facilitating advanced analyses and decision-making processes within the realm of PV technology [35].

In the following subsections, the full range of possible outcomes for each device is shown along with the comparison of the panel architectures, generation types, the analysis of the grid emissions' impact, and the most contributing process in cell production.

3.1. Distribution of the environmental impact of different photovoltaic technologies

The possible combinations for the panels' compositions were summarized in a distribution across all the considered impact categories and can be seen in Fig. 8. The results are represented in 1 m^2 of a module and 1 kWh of produced energy. In regards to the results per 1 m^2, the perovskite tandem module has the highest impact across all the categories which may be influenced by its integration with silicon cells; silicon production is energy-intensive and thus contributes significantly to environmental impacts, especially in categories such as climate change and fossil depletion. In contrast, the organic panel demonstrates the lowest impact on average in all the categories due to simpler manufacturing using solution-based processes that involve lower temperatures and require less energy. When it comes to the impact per 1 KWh, the highest impact is attributed to the CIGS modules, while the lowest can be attributed to CdTe on average. This is due to a combination of factors including a low conversion efficiency of around 10 % as well as, relative to the CdTe cell, a more intensive cell manufacturing process.

Regarding the distribution of the impacts, it can be seen that it varies across different categories. As such, the distribution of CIGS panels in terms of ionizing radiation is the highest, which can be explained by using rare and hazardous materials that are often involved in the production of CIGS panels. Materials such as indium and gallium, as well as the synthesis of the CIGS layer itself, can lead to higher levels of ionizing radiation compared to other PV technologies. This is reflected in the wider distribution and higher median values for CIGS in the ionizing radiation category.

Furthermore, the distribution of environmental impacts for cadmium telluride (CdTe) panels shows significant variability in categories such as terrestrial acidification and human toxicity. This is likely due to the use of cadmium, a toxic heavy metal, which can contribute to these impacts if not properly managed during production, usage, and recycling stages.

While perovskite tandem PVs show potential for high efficiency, they currently have a broad distribution of impacts due to the inclusion of the silicon cell and varied and evolving methods of their synthesis, which can involve different solvent and material choices leading to a range of environmental consequences.

The distributions are also multimodal indicating that there are discrete choices to the construction of the devices. These discrete choices influence the overall impact of each metric substantially. Looking deeper into one impact category, global warming potential, the influential factor is the electricity source for the production of the cell, which is discussed in further detail below.

3.2. Comparison of system types and components' contribution

In Fig. 9, the embodied carbon associated with various panel system types discussed in Section 1.3 can be seen. Along with the system types, the contribution of the components is presented. All the presented panels are configured choosing Europe as a location, as it represents the best case from the perspective of the electricity grid used for manufacturing.

A flexible thin film panel notably has the lowest embodied GWP. This can be explained by the low-carbon manufacturing process of a thin film semiconductor, in this case, CdTe. Considering the crystalline-based system types, the silicon cell has the highest contribution to the embodied GWP of a panel. It can be explained by the carbon-intensive process of cell production. For instance, the production of silicon cells involves mining and extracting raw materials such as quartz, which is an energy-intensive extraction process. Besides that, silicon cell manufacturing requires high-temperature processes and energy-intensive steps, leading to substantial energy consumption and related GHG emissions. The mounting system represents the second most significant contributor to the environmental impact of a PV panel, primarily due to the substantial amount of aluminum required for its construction.

Apart from the cell's contribution to the embodied impact, it's worth noting that the mounting system plays a significant role, accounting for a substantial share, ranging from 11 % to 42 %. This can be attributed to the manufacturing process of aluminum utilized in the mounting system. Additionally, another component with a substantial contribution to the embodied GWP is the inverter. The relatively high embodied GWP of inverters can primarily be attributed to the complexity of their electronics.

3.3. Comparison of the panel architectures

In Fig. 10, the comparison of CdTe panels assembled in Europe and China can be seen. The selected materials for the components can be seen in Table 1. The difference between the two systems assembled in different locations is 19 %. When the electricity for assembly is not considered, the difference is 6 %, which is explained by the components produced in Europe versus those that are produced outside. The difference can be associated with the technologies used, raw materials, manufacturing practices, and energy sources employed during production.

In Fig. 11, the results for CdTe panels with two assemblies' glass-glass and polycarbonate-backsheet are presented. The components were produced in Europe, and the materials used for these components are listed in Table 2. A difference of about 12 % can be observed.

3.4. Impact of grid emissions

To be able to understand the most influential processes in PV production, an analysis of the example of a monocrystalline PV panel produced in Europe was performed in Fig. 12. Considering GWP as an environmental indicator, the production of silicon, particularly single crystal and solar grade, is the largest contributor to the environmental impact. This indicates that advancements or optimizations in silicon manufacturing could significantly reduce the overall impact. Notably, we found that the electricity mix emerges as the most influential parameter in PV wafer production. The type and source of electricity play a crucial role, as regions with a cleaner energy mix can potentially significantly lower the GWP of the production process. Another study has also shown the importance of reporting the electricity mix while conducting LCA of PVs (V [14]).

Fig. 13 shows the associated impact of the panel manufacturing

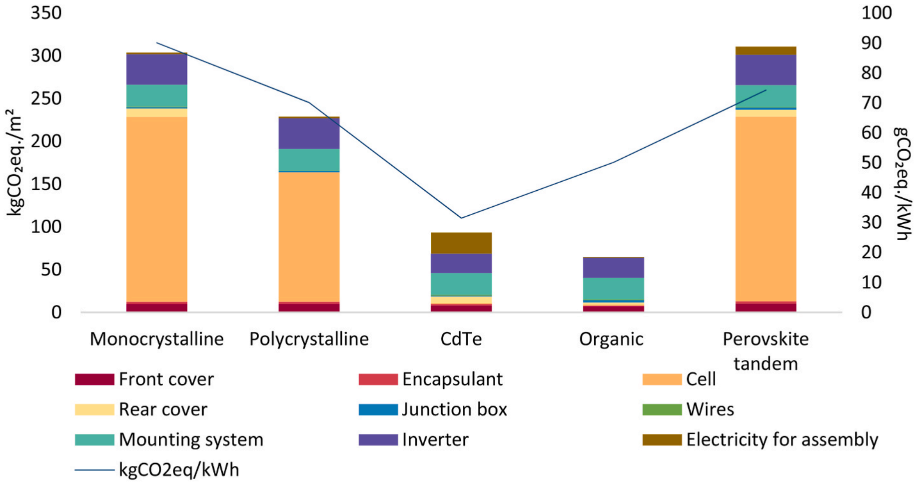


Fig. 9. Embodied GWP of different European-produced panel system types and components' contribution (the value above the bar chart represents the results in $kgCO_2eq./kWh$ assuming 1000 kWh/m^2 per annum, a 25-year lifetime, and a 75 % performance ratio).

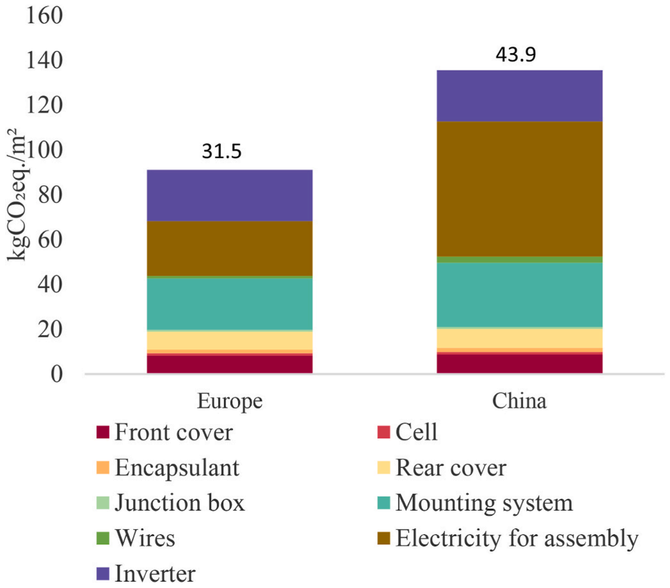


Fig. 10. Comparison of CdTe panels assembled in Europe and China (the value above the bar chart represents the results in $kgCO_2eq./kWh$ assuming 1000 kWh/m^2 per annum, a 25-year lifetime, and a 75 % performance ratio).

Table 1
Selected materials for the comparison of CdTe panels, RER – Europe, RoW – Rest of the world, CN - China.

Component	Material	Production location for the panel assembled in Europe	Production location for the panel assembled in China
Front cover	Polycarbonate	RER	RoW
Transparent conducting oxide (TCO)	Indium tin oxide	RoW	RoW
Cell	CdTe + CdS	RoW	RoW
Encapsulant	Ethyl vinyl acetate (EVA)	RER	RoW
Rear cover	Polyvinyl fluoride (PVF)	RoW	RoW
Junction box	Glass fibre reinforced plastic	RER	RoW
Wires	Copper + wiring	RER	RoW
Mounting system	Aluminum wrought alloy	RER	RoW
Electricity for assembly	Electricity medium voltage	RER	CN
Inverter	0.5 piece, 0.5 kW	RER	RoW
Frame	Aluminum profile	RER	RoW

process shown in Fig. 2. The result is shown as a cumulative impact and relative contribution of each process. As can be seen, the ingot formation is the most carbon-intensive process. That can be associated primarily with the high energy requirements for melting and crystallizing silicon. The need for high-purity silicon necessitates energy-intensive purification processes, while the manufacturing complexity and material losses during ingot trimming contribute to its significant carbon footprint. The wafer manufacturing, module assembly, front and rear covers, and the mounting system appear to have similar relative contributions to the overall embodied impact of a solar PV system.

4. Discussion

The present study provides a comprehensive analysis of the detailed embodied environmental implications of PV systems using a novel parametric calculator for assessing the impact of configured PV panels utilizing a per-square-meter metric. An important observation arises when comparing PV systems in terms of their GWP per kilowatt-hour ($kgCO_2eq./kWh$) of produced electricity, which leads to the conclusion that the embodied impact of PV panels has a great significant influence on their environmental life-cycle performance.

The embodied impact is represented through emissions intensity in $kgCO_2eq./kWh$ serves as a valuable metric and allows easy comparison with the local electricity grid for an analysis of a carbon payback time. While this functional unit of reporting is common in energy research, we evaluate the impact categories per square meter to ensure comparability with other construction materials, as well as between other photovoltaic modules.

A common practice within the field is to use a value range of solar irradiation on the surface, often of 800–1000 kWh/m^2a, to determine what parts of a surface to exclude from potential installation or analysis [36]. This method allows for a quick assessment of potential financial and energy return on investment. We believe that the configurator output of emissions intensity plotted against the solar irradiation on a surface provides another avenue by which to determine this threshold value. However, the embodied impact calculated using this metric may not accurately reflect the actual environmental burden associated with

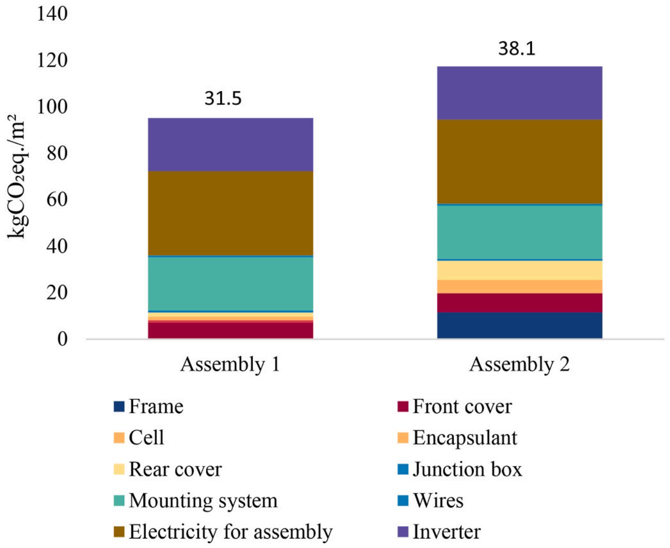


Fig. 11. Comparison of CdTe panels with different assemblies (RER) (the value above the bar chart represents the results in kgCO_2eq./kWh assuming 1000 kWh/m^2 per annum, a 25-year lifetime, and a 75 % performance ratio).

the production and installation of PV systems in all contexts. Interpretation of the results should therefore be approached with caution, recognizing the uncertainties inherent in the assumed electricity generation.

In addition to emissions, cost is another crucial parameter that needs to be considered when selecting a PV panel. Several studies have examined the costs associated with PV panels [37,38]. However, unlike the environmental impact assessment, cost evaluation is highly dependent on the specific location, and it is often difficult to adapt it to other regions. The cost analysis of PV panels involves considering various factors such as government policies, market conditions, and local energy prices that are region-specific. However, by incorporating these considerations into the assessment, stakeholders can make more informed decisions regarding PV panel selection.

The present findings are relevant for estimating the environmental impact of a PV panel. However, to comprehensively evaluate the panel's environmental impact, a complete LCA must be conducted. Expanding the analysis to include a comprehensive LCA will enable the estimation of additional important factors such as the carbon payback time and the balance between embodied emissions and operational savings. Besides that, such an assessment will allow the consideration of the future electricity mix to align with the long-term EU goals of decarbonization as well as addressing climate change. This analysis will be performed in future work.

This study shows that the most influential parameter in the embodied impact of PV is the electricity mix. Therefore, it becomes feasible to easily estimate the environmental impact of a PV panel by applying the electricity mix of a country or region (Fig. 14). This raises pertinent questions regarding the strategic positioning of PV production facilities in regions characterized by cleaner energy sources. However, this imperative extends beyond the environmental considerations and encompasses broader socio-economic and geopolitical questions.

While assessing the PV deployment from a global perspective, it is crucial to look at it from the environmental, economic, and social implications of where PV panels are produced, where they are needed, and where they will be most effective. Fig. 15 presents the resource availability from the perspective of silicon production, global electricity demand, and solar irradiation.

While regions with high silicon production have the industrial capacity to manufacture solar panels, these aren't always the areas with the highest solar irradiation, which means they might not be the regions that could most efficiently harness solar energy. The results indicate that regions with less developed infrastructure, but high solar irradiation could benefit from international investment to develop their solar capacity, addressing both local energy needs and global sustainability goals. Future research should focus on the evaluation of the raw material extraction, PV deployment, and the processes in between to underscore that solar panels can not only be produced sustainably but also be made available in regions where they can make the most significant impact on reducing carbon emissions and meeting energy demands.

5. Conclusion

In this study, we present an open-source database comprising comprehensive information on the environmental impact of PV panel components. The database covers various PV types and includes multiple environmental impact indicators essential for evaluating photovoltaic systems. It is geographically localized to specific locations where component production is viable, including the implications on the environmental impact.

In addition to the database, we have created a simplified configurator that automates the component selection process using the available locations. This calculator offers architects, engineers, and planners a convenient means to estimate the embodied impact of their PV systems with a higher level of detail. This will allow end users to conduct efficient and accurate assessments of their PV systems' embodied impacts, providing valuable insights for sustainable design practices. The results also show that depending on the PV design, achieved resulting GWP can span a broad range. Therefore, careful selection of the components and production location is needed to reduce the embodied impact.

Limitations

In the current study, end-of-life and replacement of the PV components are not included. Factors such as recycling, proper disposal, waste management, and potential emissions during the decommissioning process are crucial to understanding the total environmental impact of PV panels. The end of life and potential recycling of the panels are not

Table 2
Selected materials for the components in Fig. 11.

Component	Assembly 1	Assembly 2
Front cover	Polycarbonate	Glass
Transparent conducting oxide (TCO)	Indium tin oxide	Indium tin oxide
Cell	CdTe + CdS	CdTe + CdS
Encapsulant	EVA	Epoxy resin
Rear cover	PVF	Glass
Junction box	Glass fibre reinforced plastic	Glass fibre reinforced plastic
Wires	Copper + wiring	Copper + wiring
Mounting system	Aluminum wrought alloy	Aluminum wrought alloy
Electricity for assembly	Electricity medium voltage	Electricity medium voltage
Inverter	0.5 piece, 0.5 kW	0.5 piece, 0.5 kW
Frame	Aluminum profile	Frameless

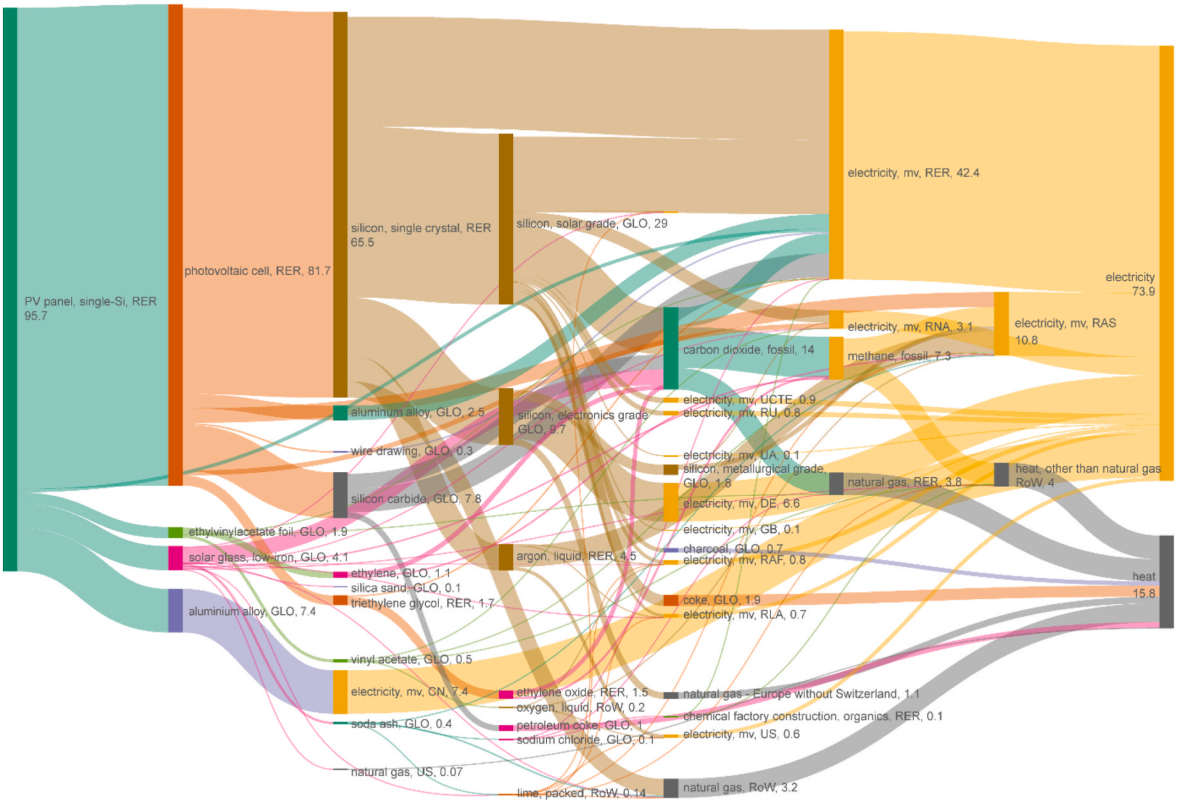


Fig. 12. The influential processes (in percentage) in the Single Si panel production produced in Europe. RER – Europe, GLO – Global, RNA – North America, RAS – Asia and Pacific, RoW – Rest of the world, RLA – Latin America and the Caribbean, RAF – Africa, UCTE - Union for the Co-ordination of Transmission of Electricity, CN – China, DE – Germany, GB – Great Britain, RU – Russia, UA – Ukraine, US – United States.GHG emissions associated with the manufacturing process (values in kgCO2eq/m^2).

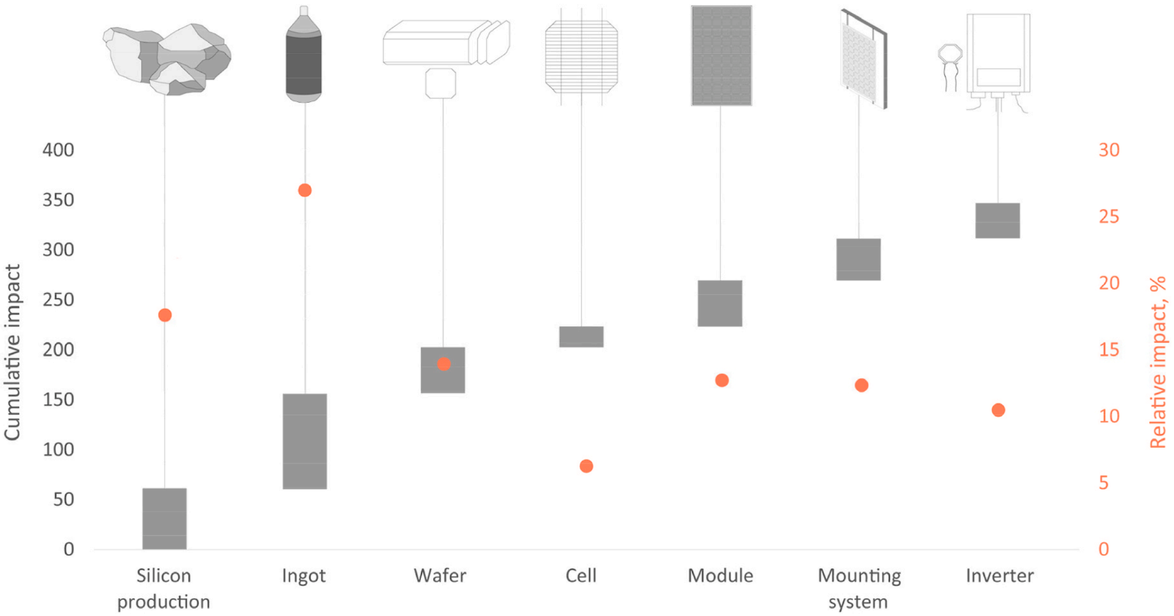


Fig. 13. Panel manufacturing process and associated GHG emissions (kgCO$_2$eq./m^2).

considered as they highly depend on the selected recycling technique. However, the recycling potential of the components will be included in future work.

The current database includes the materials commonly applied for PV production. As such, new technological improvements associated with the material' replacement or reduction in quantities are not considered in this study. The replacement of certain components, for instance, an aluminum-based mounting system could be replaced by a timber alternative [39], potentially leading to a lower embodied impact. Nonetheless, the adaptability of our database allows for seamless enrichment, facilitating the incorporation of emerging technologies and their corresponding environmental implications in future assessments.

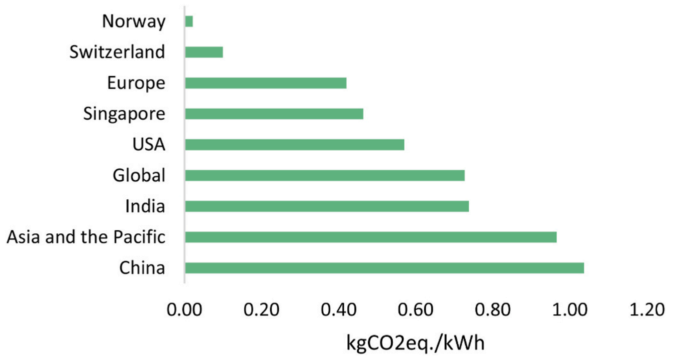


Fig. 14. *Carbon intensity of the electricity mix of several regions, data source – Ecoinvent 3.10* [29].

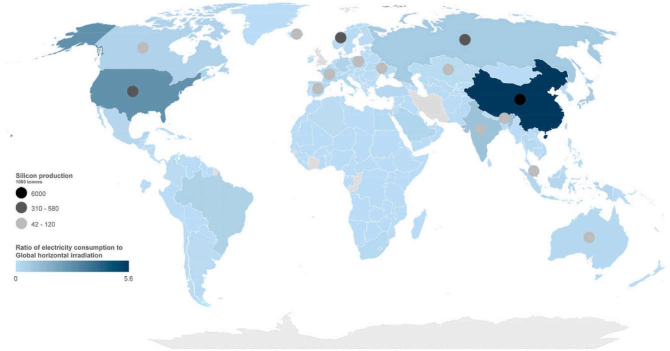


Fig. 15. *Global distribution of silicone deposits, solar insolation, and total electricity demand* ([41,42,45]).

Within the database, diverse geographical locations are represented depending on the availability of data. Nevertheless, the potential for further expansion exists, driven by ongoing data collection efforts and advancements in PV technology research. The database, configurator, as well as associated code, are open-source and available online [40].

CRediT authorship contribution statement

Alina Galimshina: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Justin McCarty:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christoph Waibel:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Arno Schlueter:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Alexander Hollberg:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT V4 and Grammarly in order to improve the readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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