

Ground-mounted or residential rooftop photovoltaic plant – European production or Chinese production: which is the most environmentally sustainable system? A case study in Italy

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Abstract. In recent years, decarbonization policies have pushed for a significant increase in renewable energies for power generation applications. European strategy aims to bring online over 320 GW of solar photovoltaics by 2025 and almost 600 GW by 2030. In this context, it is not only important to figure out the main hotspots of PV system but also to understand which are the best configurations from an environmental point of view. The analysis proposed in this paper aims to compare the environmental benefits of producing 1 kWh through two different system configurations: a ground-mounted PV plant (84 MW) and a residential rooftop PV plant (3 kW). In particular, the PERC (Passivated Emitter and Rear Cell) technology is investigated. In addition, in order to assess the influence of the energy mix used in the production of the PV components (mono-Si ingot, wafer, cell and module) on the LCA results, two different production sites are explored, i.e., in China and in Europe.

Keywords: Climate change / photovoltaic system / PERC / environmental impacts / life cycle assessment / carbon footprint

1 Introduction

Renewable sources play a fundamental role in the decarbonization of the energy and transport sectors, where the use of renewables has become increasingly widespread in recent years.

Specifically, 37.78 GW of renewable energy systems were installed in Europe in 2021, with an increase of 8% compared to 2020, mainly due to new installations of photovoltaic plants (+25.7 GW) [1]. The same situation can be found in Italy, where 944 MW of new photovoltaic systems have been installed in 2021 [2].

The considerable growth of the Italian photovoltaic sector is attributable to the ease of installation and versatility of the PV plants, which, unlike other technologies, can be installed directly on private properties, both residential and industrial. In fact, if during the years of significant expansion of the photovoltaic sector (from 2008 to 2012) there was a simultaneous increase in both ground-mounted and rooftop installations, in 2022 we observed a greater diffusion of non-ground-mounted installations (16,661 MW installed on rooftops compared to 8,403 MW installed on the ground) [3].

In terms of technologies currently installed in Italy, polycrystalline silicon modules are still the most widespread technology (approximately 65% in 2022), followed by monocrystalline silicon (30%). The amount of amorphous silicon (2%) and thin-film technology is negligible [3].

Monocrystalline silicon technology includes a wide range of cell types, distinguished by the position of contacts or specific treatments designed to enhance cell efficiency and make it more suitable for specific installations. Currently, the most commercialized technology (Fig. 1) is the Passivated Emitter Rear Cell (PERC) technology which accounts for 78% of the global market in 2022.

The PERC cells reduce the rear-surface recombination and improve rear-surface reflectivity [5]. In addition to increasing the solar cell's ability to capture light and reducing the electron recombination, passivation layer allows to keep the cell's temperature stable. Normally, one of the phenomena that leads to a reduction in the efficiency of a photovoltaic cell is the increase in its temperature due to the absorption of wavelengths. This layer reflects wavelengths outside of the cell. Figure 2 shows the structure of a standard Aluminum Back Surface Field (Al-BSF) cell and a PERC cell in both mono-facial and bifacial configurations.

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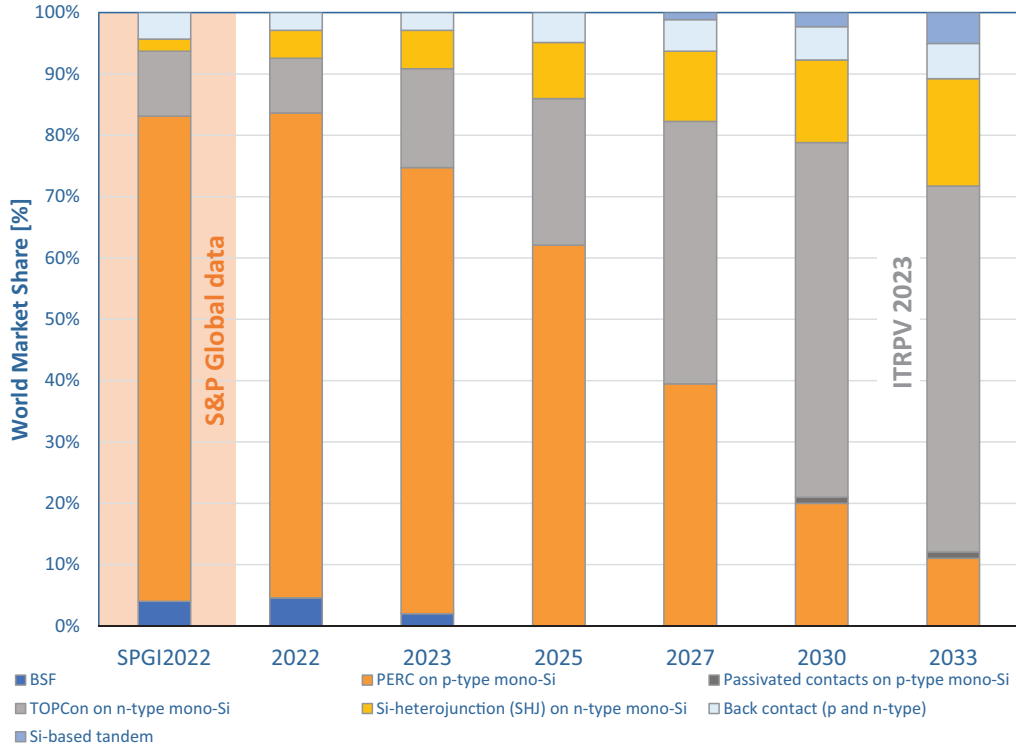


Fig. 1. World market share for different cell technologies [4].

Many existing studies focus on the LCA of Al-BSF technology, which is almost no longer produced [7–9]. The recent literature is mostly focused on the Life Cycle Assessment of new materials adopted for cell production such as perovskite, but there is still a lack of literature on new developments in silicon module design. Regarding PERC technology, despite its potential, only few studies have analyzed the environmental impact of this technology. Both bi-facial and mono-facial PV cells have been considered [10–12]. These studies consider different wafer sizes, M2, M6 and M12, and in some cases three different types of Si feedstock, i.e. Electronic Grade Silicon, Solar Grade Silicon and Upgraded metallurgical grade-Si. [11]. Furthermore, there is also a noticeable deficiency in literature regarding the comparison among different types of PV plant which, considering the multitude of possible applications, is fundamental to analyze [13]. In general, given the rapid expansion of the PV sector, it is essential that different PV systems and technologies are thoroughly investigated to identify the hotspots of the entire PV system lifecycle and assist decision makers.

In this context the present study aims to evaluate the environmental impacts of a variety of PV systems based on PERC technology.

The potential environmental impacts have been assessed using the Life Cycle Assessment (LCA) methodology, which allows evaluating environmental burdens by considering a wide range of impact categories, with the most well-known being “climate change”. Today, the LCA methodology is one of the best tools to support the implementation of interventions and policies that ensure sustainable development.

In an LCA analysis, the life cycle of products, activities, processes, and services is examined using the “cradle-to-grave” approach through four main phases:

- Definition of study objectives and the scope of application;
- Compilation of an inventory of inputs (materials, energy, and natural resources) and outputs (emissions to air, water, and soil) of the system;
- Assessment of potential impacts associated with this inventory;
- Interpretation of the results obtained to identify the most favorable strategies from an environmental perspective.

In this framework, the current analysis aims to understand the environmental benefits of producing 1 kWh_{AC} through two different plant configurations: a ground-mounted PV plant (84 MW, which is the size of the plant investigated in the GOPV project [14] and corresponds to the 90th percentile of the proposed new ground mounted PV plants in Italy [15]) and a rooftop PV plant (3kW, which is the typical size of a residential rooftop installation in Italy [16]). The analysis assumes the use of PERC (Passivated Emitter and Rear Cell) technology, among the most efficient on the market, in both the utility-scale and rooftop case studies. Both case studies are located in Catania (South Italy, characterized by an irradiance level of 1,819 kWh/m²/year) and for each of them the entire life cycle is considered, from the raw material extraction to the plant decommissioning and disposal. In addition, a sensitivity analysis is performed to better understand the contribution of possible plant

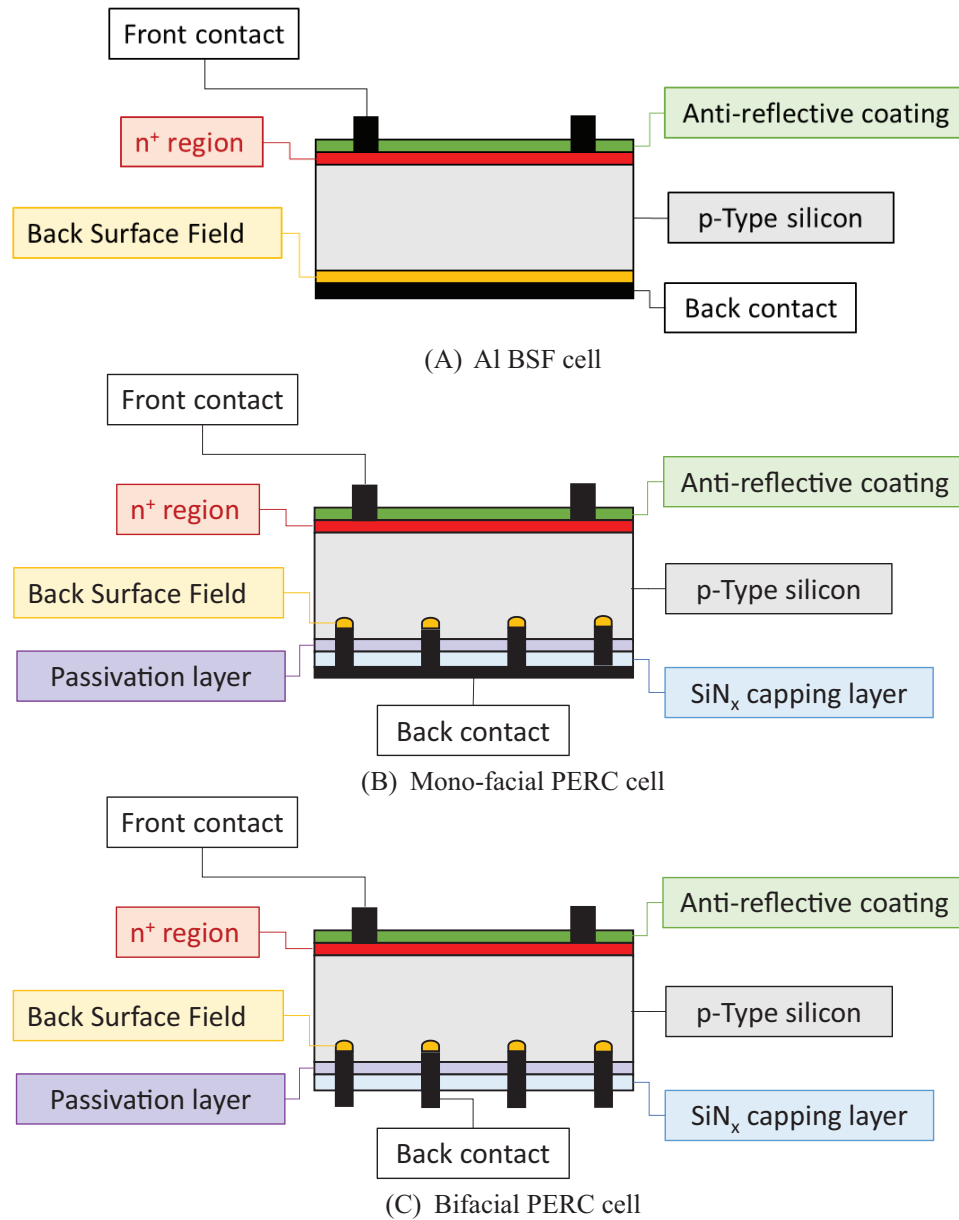


Fig. 2. Structure of an Al-BSF cell (A), mono-facial PERC cell (B) and bifacial PERC cell (C) [6].

configurations on the LCA results; in particular, three different module orientations (south, west and east) are considered for the rooftop plant and two different module supports (i.e., mono-axis tracker and fixed tilt support) for the ground-mounted plant. Furthermore, in order to assess the influence of the energy mix used in the production of the PV components (mono-Si ingot, wafer, cell and module) on the LCA results, two different production sites, i.e., China (the current top solar PV manufacturer in the world [17]) and Europe, are examined.

Finally, the last section compares the results obtained with the existing literature and the impacts generated by other technologies.

2 Materials and methods

The potential environmental impacts of the photovoltaic plants were assessed by applying the Life Cycle Assessment methodology. Life Cycle Assessment (LCA) is a quantitative methodology standardized by ISO 14040 [18] and ISO 14044 [19].

LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave). According to ISO 14040, an LCA study is consist of four phases: Goal and Scope

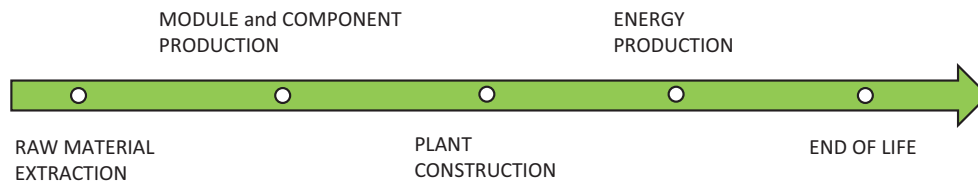


Fig. 3. Steps of the Life Cycle considered in the analysis.

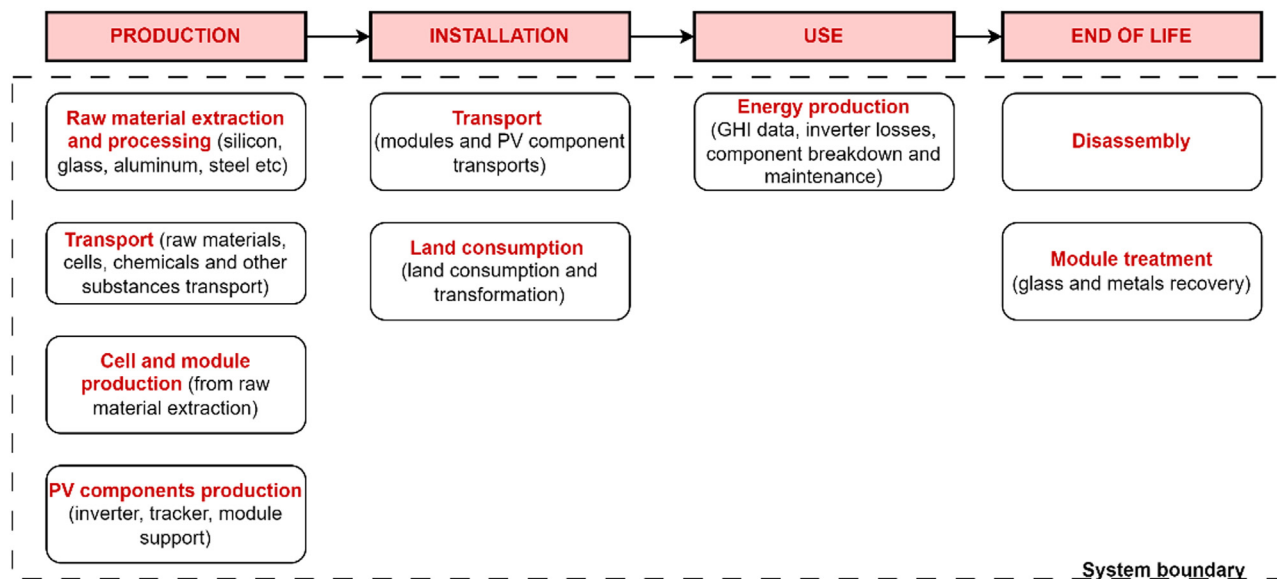


Fig. 4. System boundary.

definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation, deeply described in the following sections.

2.1 Goal and scope definition

The main goal of this study is to understand the potential environmental benefits of producing 1 kWh_{AC} by two different types of PV plants, i.e., a utility-scale PV plant and a rooftop PV plant. The study also intends to investigate the advantages and disadvantages of relocating the production of innovative photovoltaic technologies (from mono-Si ingot manufacturing to module assembling) in Europe, considering three different scenarios:

- Scenario A where modules, cells and wafers (namely from metallurgical grade silicon to wafer) are produced in China;
- Scenario B in which wafers are produced in China while modules and cells are produced in Europe;
- Scenario C in which modules, cells and wafers are produced in Europe.

The impacts are evaluated considering the entire life cycle of the plant (from raw material to end of life) in order to identify the main critical processes (Fig. 3). It is important to emphasize that, due to the lack of specific information, the end of life only considers the treatment of the module.

The functional unit (FU) adopted, according to the IEA guidelines [20], is 1 kWh_{AC} produced by the PV plant. This choice makes it possible to compare the two plants,

which are characterized by different power (84 MW utility-scale plant and 3kW rooftop plant), with other technologies for energy generation, providing an analysis of the main strengths and weaknesses of the PV technologies. Regarding the system boundary, a cradle-to-gate approach has been adopted, which includes all the life cycle of the plant from raw material extraction and components production to end of life (Fig. 4). Specifically, the analysis considers:

- Raw material extraction (e.g., silicon, aluminum, steel).
- Manufacturing and component production. In the case of wafer, the study includes all the steps of the supply chain, from silica extraction to wafer production.
- Transport associated with inverters, module supports, modules and cells.
- Land consumption due to the plant construction. Consumption associated with machinery used to construct the PV system and cables are outside the system boundary.
- End of life of the module, while the end of life of inverter and structure are not considered in the study.

Concerning the LCA model, the data adopted in the analysis were acquired thanks to the collaboration with some Italian companies that produce and market PERC modules, which provided data regarding cell and module, and also thanks to the participation in the Europe GOPV project [14], whose consortium includes photovoltaic operators, inverter and tracker

Table 1. Modules support structure technical data.

General information	Mono-axial tracker	Fixed-tilt structure
Type	Portrait tracker	Portrait structure
PV-Modules quantity per support	26	26
Numbers of poles	5	5
Dimensions (m)	14 × 4.2	14 × 4.2
Lifetime (y)	>30 yr	>30 yr
Actuator type	Linear	–
Actuator lifetime	40 yr	–
Lifetime of printed wiring board	>30 yr	–
Energy consumption	10.95 kWh/y/tracker	–
Weight	1070 kg (electric motor excluded)	962 kg
Materials and components		
Weathering steel Poles weight	303.86 kg	273.47 kg
Weathering steel Beam weight	302.82 kg	272.54 kg
Weathering steel Brace weight	330.57 kg	297.51 kg
Other components made in weathering steel	122.54 kg	110.29 kg
Aluminium rivets	8.62 kg	8.62 kg
Electric motor	6 kg	–

Table 2. Main information regarding the utility-scale inverter.

	Technical data
Power (kW)	166
Number	426
Lifetime (y)	17

manufacturers, which allowed the acquisition of information and data concerning module support structure and inverter.

As regards the background processes the Ecoinvent v3.8 database has been adopted, while, the silicon wafer production has been modeled by using the IEA Life Cycle Inventory [21]. The report [21] provides data on the entire supply chain, from raw materials to wafer production.

The potential environmental impacts were assessed using the Environmental Footprint 3.0 method [22] considering eleven impact categories (e.g., Climate Change, Ozone depletion, Photochemical ozone formation, Respiratory inorganics, Acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial eutrophication, Land use, Resource use, energy carries, Resource use, mineral and metals). In addition, the Cumulative Energy Demand category was calculated.

2.2 Photovoltaic plant configuration

The utility-scale plant, located in Catania (South of Italy), is characterized by a capacity of 84.74 MW_{DC} and consists of 184,196 mono-facial modules with a nominal power of 460 W_p (21.16% of efficiency) which are mounted on 7,085 fixed support structures made of low-alloy weathering steel

Table 3. Main characteristic of inverter adopted in rooftop plant.

	Technical features
Model	Sunway M XS 3000 TL
Peak power (W)	3600
Weight (kg)	20.8
Rated AC power (W)	3000
Cooling system	Natural

and 426 inverters. In addition, to understand the benefits or environmental burden associated with the type of modules support structure adopted, a monoaxial tracker is also considered as a replacement for fixed tilt support.

The main technical information is shown in [Tables 1](#) and [2](#).

Focusing on the rooftop installation, it consists of 7 modules mounted on an aluminum support structure with a south-facing orientation. The LCA model considers an inverter with a nominal power of 3.0 kW ([Tab. 3](#)) which is characterized by a lifetime of 17 yr. In this case, the inventory data of the inverter were collected thanks to a laboratory test carried out at the RSE premises, which made it possible to acquire data on each individual component in terms of material, and number of components. For the rooftop case study, the module support structure was modelled by using the Ecoinvent v3.8 database.

In both case studies (ground mounted and rooftop plant) the model assumes a PV plant lifetime equal to 30 yr as recommended by the IEA guideline [20]. Additional information regarding the Bill of Materials of the inverter is available in the Supplementary material (Tabs. S1–S3).

Table 4. Electricity production.

Plant	Period	Production (MWh)
Utility scale plant (module at fixed tilt)	1 yr	136,894.88
	30 yr	3,754,400.10
Rooftop plant	1 yr	5.27
	30 yr	145.997

2.3 Electricity production

The energy production during the operational phase is evaluated taking into account the annual irradiation (i.e., global horizontal irradiance [GHI]) at the installation site (1819 kWh/m²/y), the system losses and also the degradation rate of the module which, according to the manufacturer is 3% in the first year, 0.4% from the second to the twentieth year, and 0.5% in the following years. The irradiance data were downloaded from the PVGIS portal by selecting the SARA2 database [23]. The energy produced by the two analyzed systems is shown in Table 4.

2.4 Cell and module production

The cell production refers to all the steps involved in the supply chain, i.e., metallurgical-grade silicon from silica, polycrystalline silicon feedstock purification process (using the Siemens process), crystallization process (the Czochralski method), wafering and cell processing. The first stages up to the wafer production, due to the lack of primary data, have been modelled using IEA Life Cycle Inventory (LCI) data [21]. As regards the cell production from wafer, the LCI data (i.e., chemicals and energy consumption, emissions, and treatment processes) were provided by the International Solar Energy Research Center Konstanz (ISC Konstanz, <https://isc-konstanz.de/>). The information was deduced from a volume production of 4.2 GW/yr and refers to the manufacturing of mono-facial PERC cells (Tab. 5). The total electricity consumption was estimated by the ratio between the total annual consumption of the production lines (108,562.73 MWh) and the number of cells produced in 1 year (424,300 thousand).

Concerning the PERC module (Tab. 6), the data involved in the study were acquired from FuturaSUN an Italian company specializes in High-performance PV modules production. The data refers to production at a plant in China with an equivalent volume of 1.2 GW/year. Since the primary data used in the LCI for cells refer to an M12 (210 mm × 210 mm) PERC cell, the life cycle inventory (LCI) of the production of 72 M6 cells is assumed to be equivalent to the LCI of the production of 45 M12 cells for the purpose of this study (because the cell thickness is the same, it can be assumed that the LCI is proportional to the cell surface).

Focusing on the transport, in Scenario A, the analysis considers those used to import the module from China to Europe: 20,000 km by transoceanic ship and 950 km by

Table 5. Main technical data of PERC cell.

Efficiency	22.5%
Wafer dimension	M12–210 mm × 210 mm
Wafer thickness (μm)	170

Table 6. PERC module technical data.

Name of the module:	FU 460 M Silk Pro
Type of module:	Monocrystalline PV modules with PERC cells
Production site (city and country):	Taizhou, Jiangsu, China
Dimension:	2094 × 1038 × 35 mm
Weight:	23.6 kg
Module power (Pmax):	460 W
Module efficiency:	21.16%
Number of cells:	144 half-cut M6 cells (166 mm × 166 mm)
Performance guarantee:	25 yr

Table 7. Treatment process adopted in the module EOL dataset [21].

Treatment process for a module	Amount (kg)
Treatment, c-Si PV module	23.6
Glass cullets, recovered from c-Si PV module treatment	16.7
Aluminum scrap, recovered from c-Si PV module treatment	2.6
Copper scrap, recovered from c-Si PV module treatment	0.2

truck, according to the IEA report on Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems [21], while transportation from final harbor to power plant site is considered negligible. The study assumes that cells and modules are produced in the same plant.

The full cell and module datasets are reported in the Additional Information (Tabs. S4 and S5).

Finally, the data and information regarding the End-of-Life of modules was collected from the IEA LCI [21]. The report considers the treatment of the module's glass, aluminum and copper which account for 80% of the total module weight, while the cells and other materials such as plastics are incinerated. The EOL dataset is reported in Table 7, the dataset refers to 1 module. In this case 4.35E+06 kg and 1.65E+02 kg is treated in the utility scale PV plant and rooftop PV plant respectively.

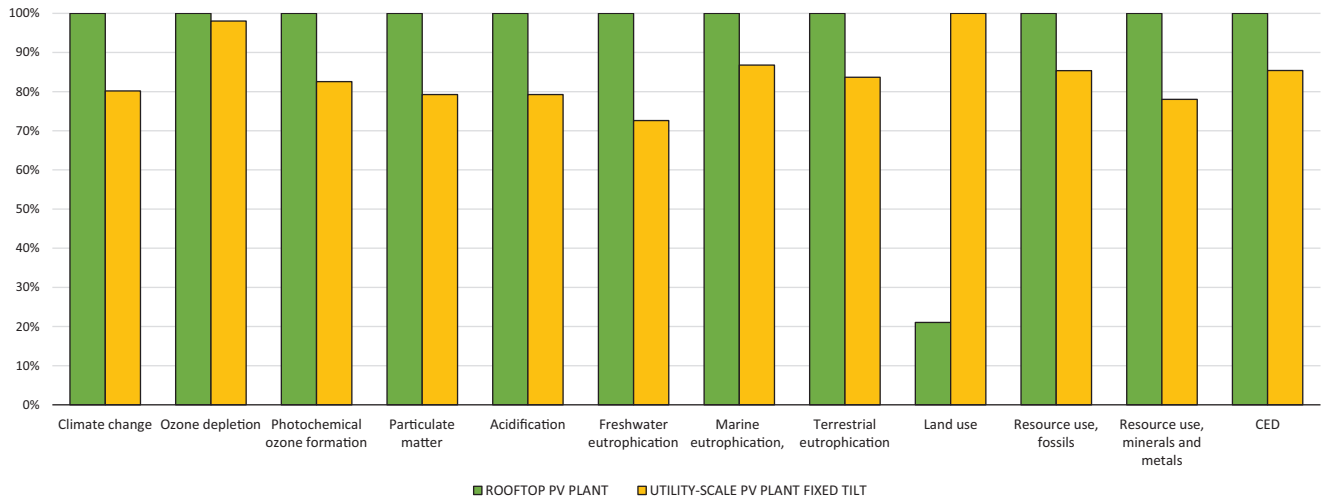


Fig. 5. Comparison of the environmental impacts generated by the two plants (ground-mounted fixed tilt PV plant and rooftop plant) located in Catania. The results are expressed per F.U and consider the following impact categories: Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Particulate Matter (PM), Acidification (A), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Eutrophication (TE), Land Use (LU) Resource use, fossil (RU_F), Resource Use, Mineral and Metals (RU_MM) and Cumulative Energy Demand (CED).

3 Results and discussion

The comparison of the potential environmental impacts associated with the energy production from a utility-scale PV plant and a rooftop PV plant is shown in Figure 5.

The results are related to the functional unit (1 kWh_{AC}) and are referred to Scenario A in which all the module production (from metallurgical grade silicon to module assembling) is in China. Both PV plants are located in Catania (South of Italy), facing south, with an inclination of 34 degrees for the ground-mounted plant and 30 degrees for the rooftop installation. The study considers twelve impacts categories in accordance with the IEA PVPS guidelines [20]. The outcomes reveal that the utility-scale plant is characterized by a lower impact than a rooftop PV plant (Fig. 5). The higher energy production associated with the utility-scale plant results in a reduction of the impacts with respect to the rooftop plant. More specifically, in the utility-scale system, the modules are installed in the optimal position in terms of tilt and orientation to maximize energy production. On the other hand, for rooftop installations, the position of the modules is constrained by the available surface area, sometimes resulting in lower production. Considering the Land Use category, the rooftop plant is the most advantageous (−79% of the impact): unlike ground-mounted installations, rooftop installations do not require any land.

Focusing on the contribution analysis (Fig. 6), it can be observed that higher impacts are associated with module production, considering the supply chain from raw material extraction to module production, which ranges from 32% (Resource use, mineral and metals) to 51% (Marine eutrophication) of the impacts in the rooftop plant (Tab. 8) and from 10% (Land use) to 58% (Marine eutrophication) of the total impacts in case of utility-scale

plant (Tab. 9). The inverter production mainly affects the Resource use, mineral and metals category in which the higher impact is generated by the electronics and the precious metals involved in the production process. Negligible impacts are instead associated with the transport, end-of-life and DC losses.

It is important to note that the study adopts a cut-off approach, this implies that material recovery processes do not bring benefits or burdens.

A detailed analysis of the impacts, in the Climate change category, associated with the module production (Fig. 7) reveals that the largest contribution is related to wafer production (59% of the module impacts). In fact, the significant energy consumption connected to solar-grade silicon production contributes to a significant increase in the environmental burdens.

3.1 Analysis of module production scenarios

The results concerning the variation of the outcomes based on the country of module production (and thus of the energy mix used), considering the entire production chain from raw material to module, are presented in this section. Specifically, the analysis considers three different scenarios (Tab. 10):

- Scenario A in which modules, cells and wafers (from metallurgical grade silicon to wafer) are produced in China;
- Scenario B in which cells and module are produced in Europe while wafers are produced in China;
- Scenario C in which module, cells production and the entire wafers supply chain (from metallurgical grade silicon to wafer) are relocated to Europe.

Due to the lack of specific information, the adopted electricity mix reflects the average Chinese and European electricity mix models based on the Ecoinvent v3.8 databases.

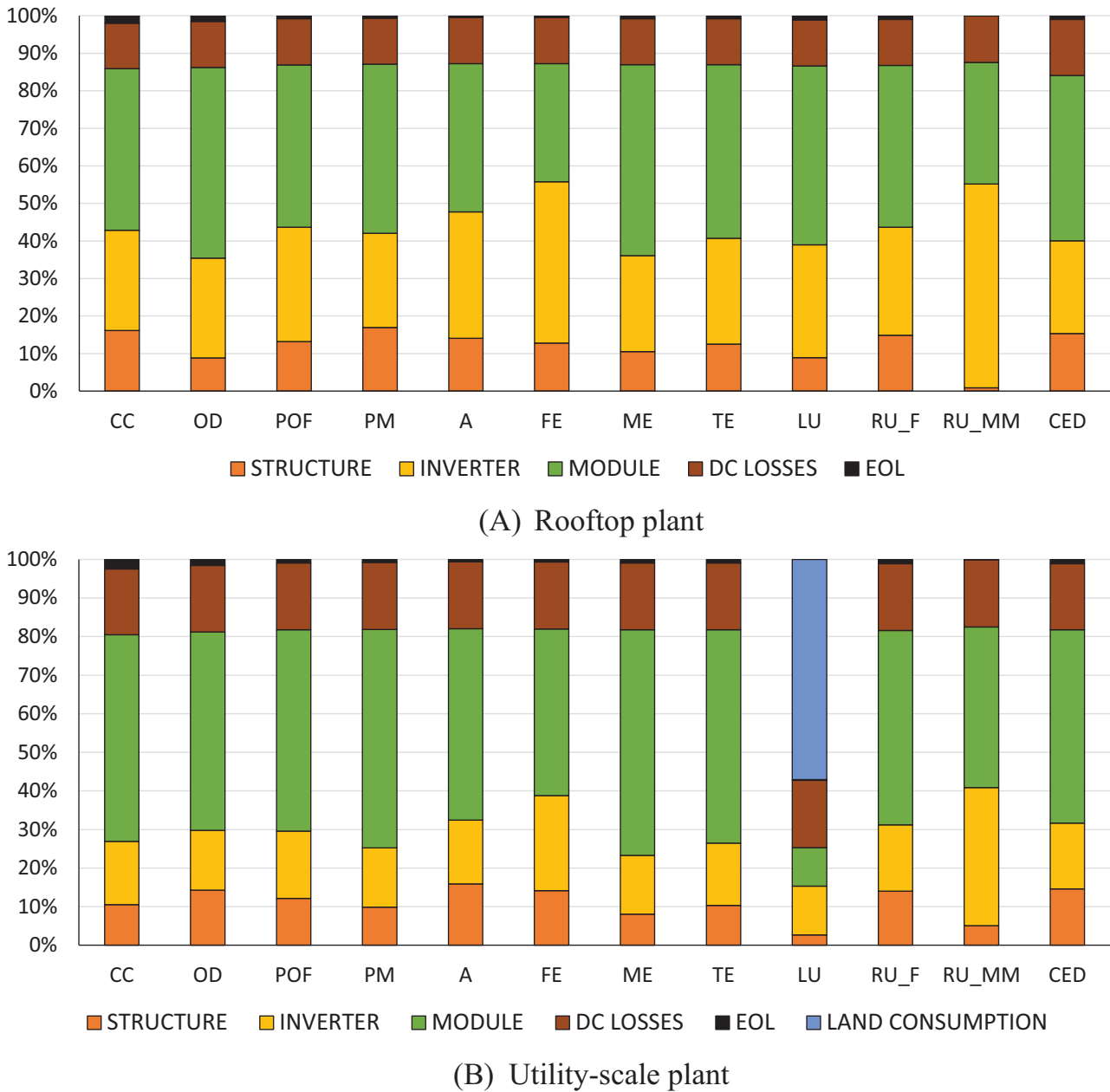


Fig. 6. Contribution analysis of the impacts for Rooftop PV plant (A) and Utility-scale plant with fixed tilt support (B). The categories analyzed are: Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Particulate Matter (PM), Acidification (A), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Eutrophication (TE), Land Use (LU), Resource Use, Fossil (RU_F), Resource Use, Mineral and Metals (RU_MM) and Cumulative Energy Demand (CED).

For what concerns the origin of chemicals and materials involved in the production process is supposed to reflect, as closely as possible, the production market associated with the location of the production site.

Table 11 shows the percentage variation of the environmental burden associated with the module production between the baseline scenario (Scenario A) and the other two scenarios analyzed (Scenario B and Scenario C). From the results, it can be noticed the impacts reduction achievable thank to the relocation of the supply-chain of module to Europe, especially in Scenario C. However, due

the lignite powerplant, in European electricity mix, Scenario B and Scenario C caused an increase of the environmental burden in the Freshwater eutrophication categories. The benefits achievable thanks to the shift of silicon supply-chain from China to other country characterized by a cleaner electricity mix are remarkable also considering the entire life cycle of the PV plants (Fig. 8). The figure shows the variation of the potential environmental impacts generated by the two scenarios (Scenario B and Scenario C) with respect to the Scenario A. The results are expressed per kWh_{AC} produced by the PV plant.

Table 8. Potential environmental impacts generated by the production of 1 kWh_{AC} through a rooftop PV plant located in Catania, characterized by a GHI of 1819 kWh/m²/y and an energy yield of 1,644 h.

Impact categories	Structure	Inverter	Module	DC losses	EOL	Total
Climate change (kg CO ₂ eq)	3.50E-03	5.80E-03	9.35E-03	2.63E-03	4.28E-04	2.17E-02
Ozone depletion (kg CFC11 eq)	1.34E-10	4.05E-10	7.74E-10	1.86E-10	2.34E-11	1.52E-09
Photochemical ozone formation (kBq U-235 eq)	1.16E-05	2.67E-05	3.79E-05	1.08E-05	6.74E-07	8.77E-05
Particulate matter (kg NMVOC eq)	2.79E-10	4.13E-10	7.40E-10	2.02E-10	1.00E-11	1.64E-09
Acidification (disease inc.)	2.24E-05	5.36E-05	6.28E-05	1.96E-05	7.38E-07	1.59E-04
Eutrophication, freshwater (CTUh)	1.23E-06	4.13E-06	3.02E-06	1.18E-06	4.44E-08	9.60E-06
Eutrophication, marine (CTUh)	3.72E-06	9.08E-06	1.80E-05	4.35E-06	2.79E-07	3.55E-05
Eutrophication, terrestrial (mol H + eq)	3.84E-05	8.64E-05	1.42E-04	3.76E-05	2.38E-06	3.06E-04
Land use (kg P eq)	8.41E-03	2.83E-02	4.49E-02	1.15E-02	1.05E-03	9.43E-02
Resource use, fossils (kg N eq)	3.46E-02	6.71E-02	1.00E-01	2.85E-02	2.23E-03	2.33E-01
Resource use, minerals and metals (mol N eq)	1.05E-08	6.32E-07	3.78E-07	1.44E-07	3.75E-10	1.16E-06
CED (MJ)	4.07E-02	7.94E-02	1.17E-01	3.34E-02	2.53E-03	2.73E-01

Table 9. Potential environmental impacts generated by the production of 1 kWh_{AC} through utility-scale plant with fixed tilt support and located in Catania, characterized by a GHI of 1819 kWh/m²/y and an energy yield of 1,616 h.

Impact categories	Land consumption	Structure	Inverter	Module	DC losses	EOL	Total
Climate change (kg CO ₂ eq)	0.00E+00	1.83E-03	2.85E-03	9.33E-03	2.97E-03	4.27E-04	1.74E-02
Ozone depletion (kg CFC11 eq)	0.00E+00	2.14E-10	2.33E-10	7.74E-10	2.59E-10	2.34E-11	1.50E-09
Photochemical ozone formation (kBq U-235 eq)	0.00E+00	8.78E-06	1.26E-05	3.78E-05	1.25E-05	6.74E-07	7.24E-05
Particulate matter (kg NMVOC eq)	0.00E+00	1.28E-10	2.00E-10	7.37E-10	2.26E-10	9.98E-12	1.30E-09
Acidification (disease inc.)	0.00E+00	2.01E-05	2.09E-05	6.27E-05	2.20E-05	7.37E-07	1.26E-04
Eutrophication, freshwater (CTUh)	0.00E+00	9.86E-07	1.72E-06	3.01E-06	1.21E-06	4.43E-08	6.97E-06
Eutrophication, marine (CTUh)	0.00E+00	2.48E-06	4.69E-06	1.80E-05	5.33E-06	2.79E-07	3.08E-05
Eutrophication, terrestrial (mol H+eq)	0.00E+00	2.64E-05	4.12E-05	1.41E-04	4.42E-05	2.38E-06	2.55E-04
Land use (kg P eq)	2.56E-01	1.21E-02	5.65E-02	4.49E-02	7.82E-02	1.05E-03	4.48E-01
Resource use, fossils (kg N eq)	0.00E+00	2.79E-02	3.40E-02	1.00E-01	3.43E-02	2.23E-03	1.98E-01
Resource use, minerals and metals (mol N eq)	0.00E+00	4.58E-08	3.24E-07	3.77E-07	1.58E-07	3.75E-10	9.05E-07
CED (MJ)	0.00E+00	3.39E-02	3.99E-02	1.16E-01	4.02E-02	2.52E-03	2.33E-01

The contribution analysis of the impacts associated with module production and related to the climate change impact category is shown in [Figure 9](#). The graphs reveal a reduction of cell (and upstream supply chain) contribution which decreases from 68% (Scenario A) to 53% (Scenario C). “Other”, includes chemicals, wastes and transport. Full results are available in the Additional Information (Tab. S6).

3.2 Sensitivity analysis on the variation of solar radiation available

Solar radiation directly impacts energy production and depends on the orientation of the modules, installation site, and type of module support structure adopted. In this section, three different configurations have been analyzed that could lead to variations in results:

- Different exposures of modules for rooftop installation (south, west and east) located in Catania.

- Different module support structure for utility-scale plant (mono-axial tracker and fixed tilt support) located in Catania.
- Comparison between a PV plant in Catania (Southern Italy) and the same one installed in Piacenza (Northern Italy). The analysis has been carried out for both ground mounted plant and rooftop plant.

3.3 Different module orientation

Analyzing the different orientations of modules in the rooftop installation it can be notice that the system with south-facing modules ensures maximum energy production and therefore lower environmental impacts compared to systems with west and east exposure ([Fig. 10](#)). The latter two exhibit very similar impacts, with a slight increase in the impacts associated with west-facing exposure.

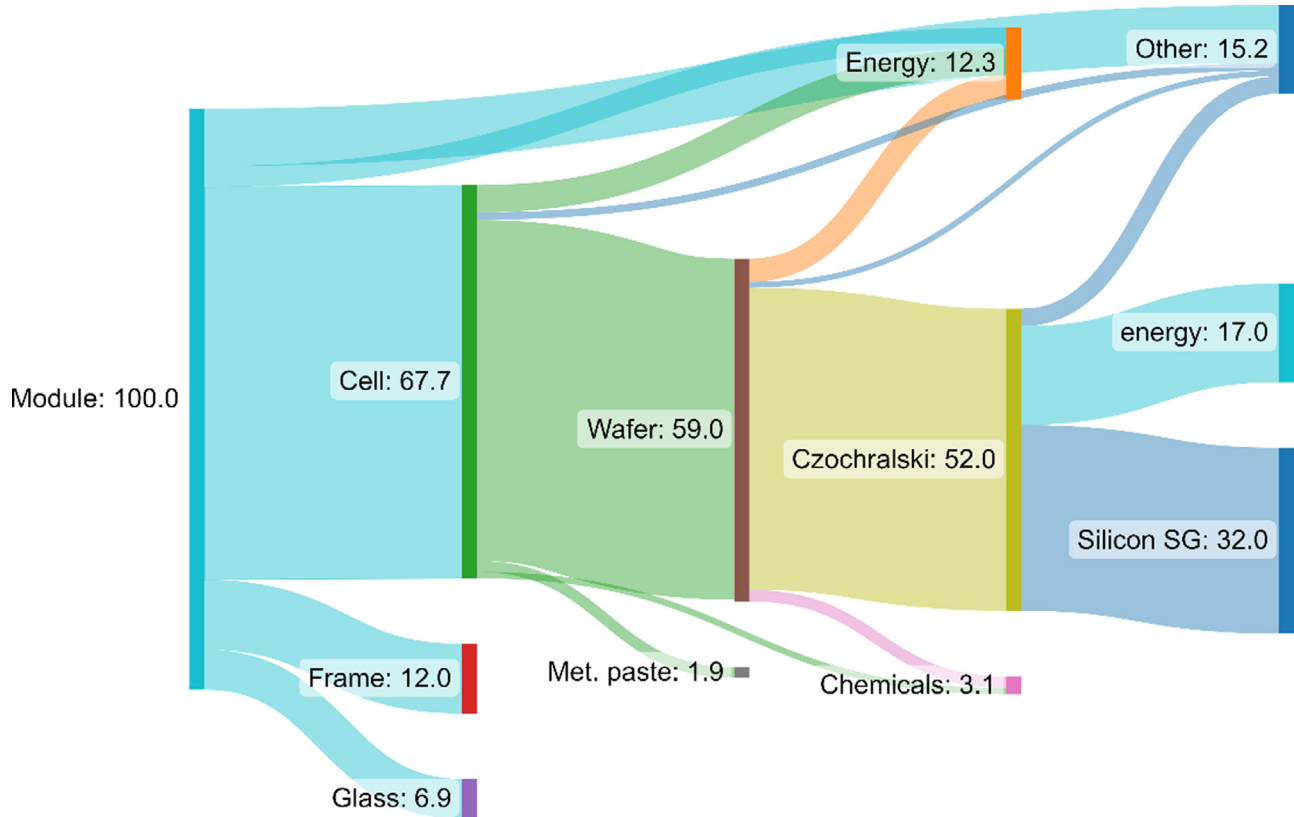


Fig. 7. Contribution analysis of module supply-chain considering the Climate change and referred to the Scenario A.

Table 10. Differences among the three scenarios investigated and where processes take place along the silicon chain.

Process	Energy consumption	Scenario A	Scenario B	Scenario C
Metallurgical-grade silicon	11 kWh/kg	China	China	Europe
Polysilicon	49 kWh/kg	China	China	Europe
Silicon ingot (Czoehralski method)	32 kWh/kg	China	China	Europe
Wafering	4.76 kWh/m ²	China	China	Europe
Cell manufacturing	5.8 kWh/m ²	China	Europe	Europe
Module assembling	4.13 kWh/m ²	China	Europe	Europe

Table 11. Analysis of the potential environmental impacts generated by producing 1 module in function of the energy mix adopted in the 3 different scenarios considered. The results are expressed as a variation of the impacts generated by the production of 1 module with respect to the Scenario A.

Impact categories	$\Delta_{AB} = (SC_B - SC_A) / SC_A$	$\Delta_{AC} = (SC_C - SC_A) / SC_A$
Climate change (kg CO ₂ eq)	−5.3%	−36.8%
Ozone depletion (kg CFC11 eq)	1.4%	8.0%
Photochemical ozone formation (kBq U-235 eq)	−5.0%	−36.4%
Particulate matter (kg NMVOC eq)	−7.4%	−47.2%
Acidification (disease inc.)	−4.3%	−33.2%
Eutrophication, freshwater (CTUh)	4.6%	32.9%
Eutrophication, marine (CTUh)	−3.5%	−25.0%
Eutrophication, terrestrial (mol H + eq)	−5.3%	−37.8%
Land use (kg P eq)	−1.3%	−14.0%
Resource use, fossils (kg N eq)	−0.8%	−12.6%
Resource use, minerals and metals (mol N eq)	0.0%	−0.1%
CED (MJ)	−0.2%	−4.8%

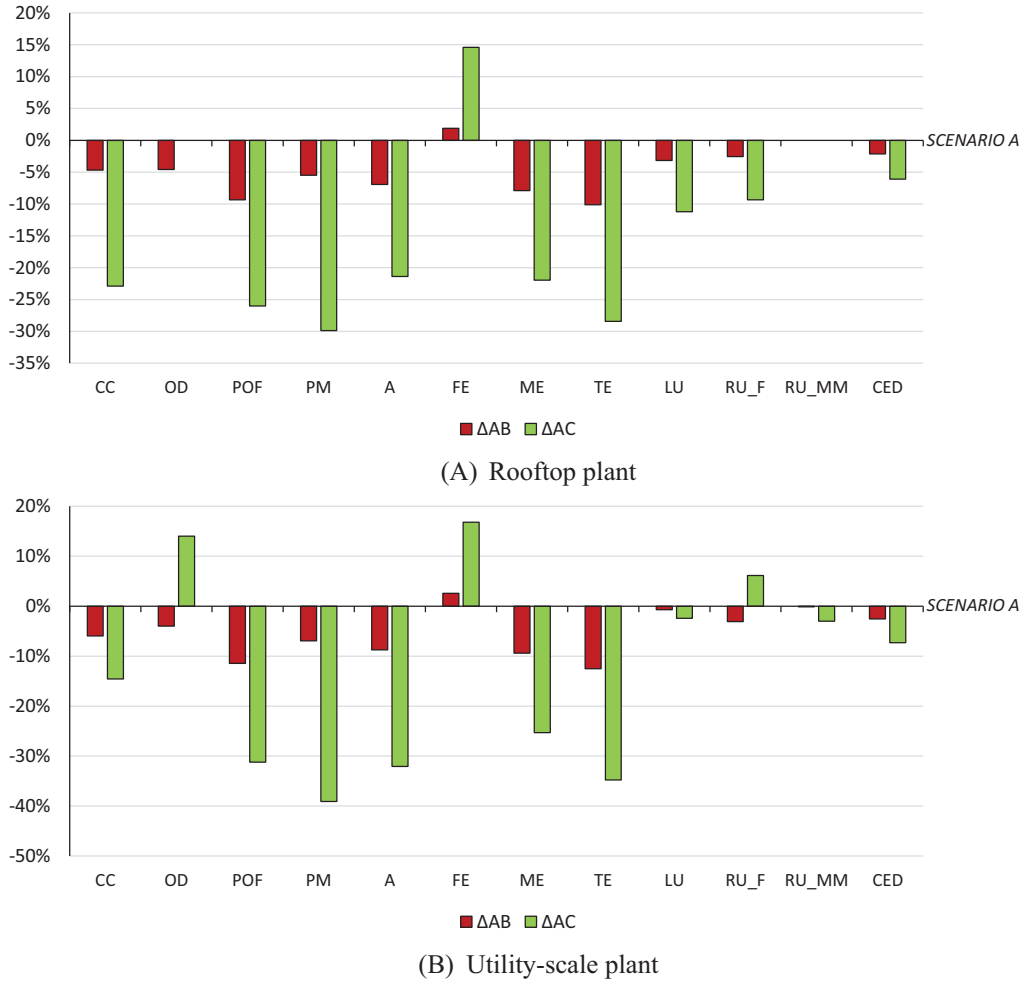


Fig. 8. Variations of the potential environmental impacts caused by the relocation of the module production according to the Scenario B and Scenario C with respects to the Scenario A. The results are referred to the 1 kWh_{AC} produced by the two plants: (A) Rooftop plant and (B) Utility-scale plant and considers twelve impacts categories: Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Particulate Matter (PM), Acidification (A), Freshwater eutrophication (FE), Marine Eutrophication (ME), Terrestrial Eutrophication (TE), Land use (LU), Resource Use, Fossil (RU_F), Resource Use, Mineral and Metals (RU_MM) and Cumulative Energy Demand (CED).

3.4 Different module supports for utility-scale plant

Analyzing the environmental burdens resulting from the use or non-use of single-axis solar tracker support structures, it is evident that the tracker not only ensures an increase in energy production but also leads to a reduction in environmental burdens.

The presence of single-axis solar trackers allows, under the conditions of this study, a reduction in environmental burdens ranging from 5% to 19%, depending on the impact category, for the Catania site (Fig. 11).

3.5 Different PV installation site

The comparison between a PV plant located in Catania (Southern Italy with a GHI of 1,819 kWh/m²) and the same one installed in Piacenza (Northern Italy with a GHI of 1,368 kWh/m²) reveals that the installation located in

Catania has the lowest environmental impacts (Tab. 12), highlighting the importance of solar radiation on the results. The table shows the overall results associated with the utility-scale plant and the rooftop PV plant located in Catania and Piacenza, and also, the variation of the results between the two locations. The variation has been calculated according to equation (1).

$$\Delta_{\text{impact}} = (I_{PC} - I_{CT}) / I_{CT} \quad (1)$$

I_{PC} and I_{CT} represent the impact generated by a plant located in Piacenza and Catania respectively.

The results obtained once again emphasize the influence of solar radiation on energy production. The energy production of a photovoltaic system is directly proportional to the GHI, which is the total radiation incident on a horizontal surface. The higher the GHI at the installation site, the higher is the energy production of the

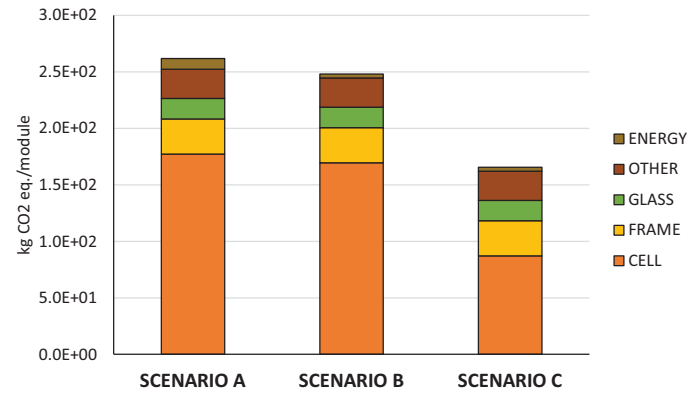


Fig. 9. Analysis of contributions in the generation of greenhouse gas emissions (climate change impact category), regarding module production. The results are expressed per module production.

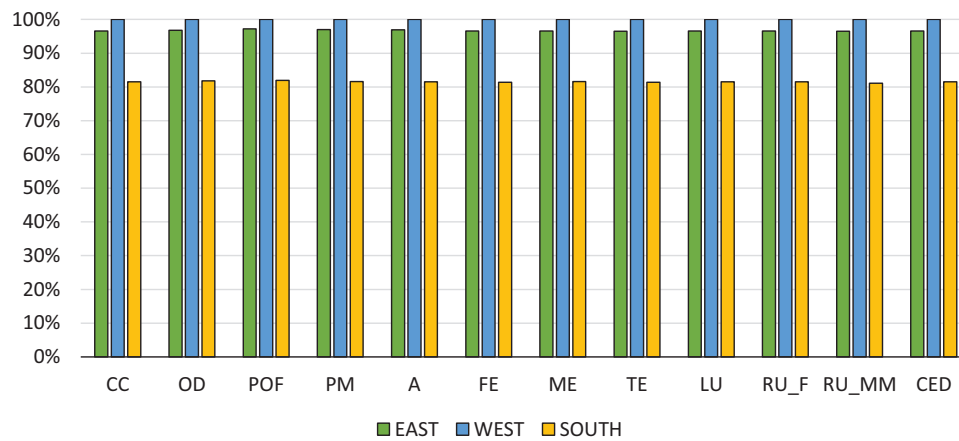


Fig. 10. Comparison of the potential environmental impacts of three different orientations for a rooftop plant located in Catania (South Italy). The results are referred to F.U. (1 kWh produced by the PV plant). The categories analyzed are: Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Particulate Matter (PM), Acidification (A), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Eutrophication (TE), Land use (LU), Resource Use, Fossil (RU_F), Resource Use, Mineral and Metals (RU_MM) and Cumulative Energy Demand (CED).

system, which means that the impacts generated during the component production and end-of-life of the system are spread over a higher energy production.

3.6 Comparison with other technologies and literature

In order to make a comparison with the data available in the literature, three studies were selected as representative of the case under consideration (Tab. 13), i.e., three studies analyzing up to date PERC PV modules.

The studies investigate both bifacial and mono-facial PERC cell and three different Si-feedstocks, which could influence the results, especially in terms of energy consumption. The studies consider three type of wafer sizes, M2 (156 mm × 156 mm), M6 (166 mm × 166 mm) and M12 (210 mm × 210 mm), and different lifetimes 25 years and 30 years. Regarding the solar irradiation, which strongly influences the results, it ranges from 1573 to 1819 kWh/m²/year. Although, a complete comparison is not possible, due to different hypothesis such as boundary conditions, Functional

Unit (FU) adopted, the obtained results in our study, at least for Climate Change Environmental Impact Category, can be considered in line with the findings of other studies.

Finally, in Figure 12 the comparison (restricted to the Climate Change impact category) between the environmental impacts generated by the production of electricity from PV plants (rooftop and ground-mounted with fixed tilt support configuration), natural gas power plant, wind turbine and the impacts associated with the European electricity mix modelled according with Ecoinvent v3.8 is shown. The decision to compare PV plants with natural gas and wind power plants stems from:

- Natural gas has a high share in the European energy mix (about 50%);
- Wind generation has been growing in recent years in Europe.

The comparison in Figure 12 shows the impacts per 1 kWh_{AC}. The values related to the PV systems are referred to Scenario A.

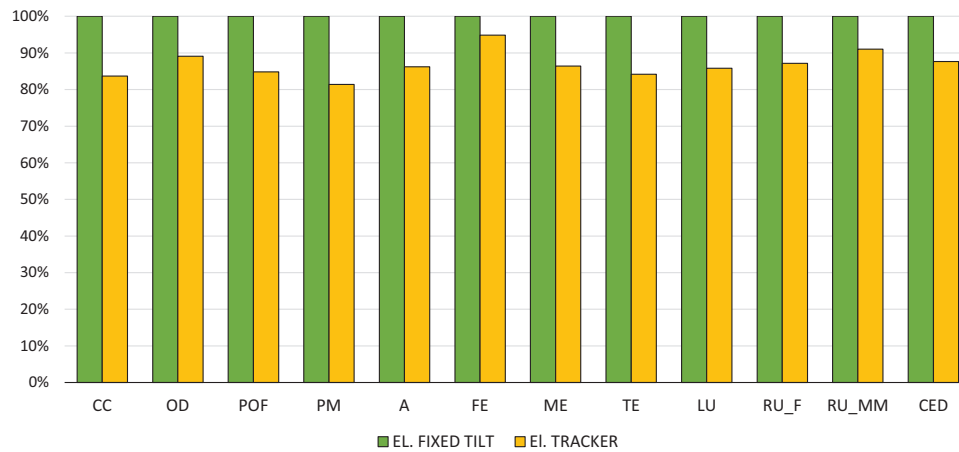


Fig. 11. Comparison of the potential environmental impacts between a PV plant with tracker and a PV plant with modules at fixed tilt. The results are referred to F.U (1 kWh produced by the PV plant). The categories analyzed are: Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Particulate Matter (PM), Acidification (A), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Eutrophication (TE), Land use (LU), Resource Use, Fossil (RU_F), Resource Use, Mineral and Metals (RU_MM) and Cumulative Energy Demand (CED).

Table 12. Sensitivity analysis on the PV location site.

	Utility-scale			Rooftop		
	CT	PC	Δ_{impact}	CT	PC	Δ_{impact}
Climate change (kg CO ₂ eq)	1.74E-02	1.95E-02	12%	2.17E-02	2.59E-02	19%
Ozone depletion (kg CFC11 eq)	1.50E-09	1.67E-09	11%	1.53E-09	1.82E-09	19%
Photochemical ozone formation (kBq U-235 eq)	7.24E-05	8.02E-05	11%	8.77E-05	1.04E-04	19%
Particulate matter (kg NMVOC eq)	1.30E-09	1.46E-09	12%	1.64E-09	1.96E-09	20%
Acidification (disease inc.)	1.26E-04	1.37E-04	9%	1.59E-04	1.90E-04	19%
Eutrophication, freshwater (CTUh)	6.97E-06	7.61E-06	9%	9.60E-06	1.14E-05	19%
Eutrophication, marine (CTUh)	3.08E-05	3.50E-05	14%	3.55E-05	4.22E-05	19%
Eutrophication, terrestrial (mol H + eq)	2.56E-04	2.86E-04	12%	3.06E-04	3.65E-04	19%
Land use (kg P eq)	4.48E-01	5.26E-01	17%	9.43E-02	1.12E-01	19%
Resource use, fossils (kg N eq)	1.99E-01	2.19E-01	10%	2.33E-01	2.77E-01	19%
Resource use, minerals and metals (mol N eq)	9.05E-07	1.05E-06	16%	1.16E-06	1.39E-06	20%
CED (MJ)	1.74E-02	1.95E-02	12%	2.73E-01	3.25E-01	19%

The outcomes reveal that the use of renewable sources instead of fossil fuel brings to a significant environmental benefit. Focusing on the technologies that use renewable sources, the three systems appear comparable.

4 Conclusion

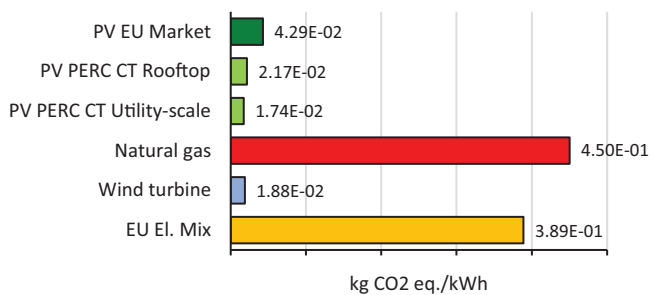
To assess the reduction of GHG emissions and other environmental impacts, achievable by the increase of PV plant in the energy sector, a Life Cycle Assessment was performed. The two plants analyzed, i.e., PV utility-scale plant and rooftop PV plant, were modelled by using primary data collected directly from the PV modules, trackers and inverters manufacturers.

Focusing on the results, the utility-scale PV plant appears beneficial compared to rooftop plant (17.4 and 21.7 g CO₂ eq/kWh respectively for Climate Change in

southern Italy case study), thanks to the higher electricity production; however, due to the land consumption necessary to build the utility-scale PV plant, the latter has a worse performance in the “land use” impact category, with an increase in environmental burdens of 79%. The analysis of the contributions of impacts for the production of 1 kWh_{AC} from a PV system reveal that the largest contribution comes from the silicon supply chain, especially from the Czochralski process to produce the silicon wafers as it is highly energy intensive. In this context, from sensitivity analysis on the location of the production site, emerges that the module assembling and in particular silicon wafer production in a country with a greener energy mix can lead to an improvement of the environmental benefits (-30% of the impacts in the Climate change category). Besides modules, electronics in the inverter is responsible for a relevant part of the environmental impacts especially in the Resource use, mineral and metals category.

Table 13. Comparison with other studies on LCA of PERC module.

	Type	Wafer size	Module (W)	Lifetime (y)	Solar irradiance (kWh/m ² /y)	F.U.	GWP (g CO ₂ eq)
Jia et al. 2021 [10]	PERC mono-facial, ground mounted	M2	340	25	1573	1 kWh	2.70E+01
	PERC mono-facial, ground mounted	M2	405	25	1573	1 kWh	2.65E+01
	PERC bi-facial, ground mounted	M2	345	30	1573	1 kWh	2.00E+01
	PERC bi-facial, ground mounted	M2	410	30	1573	1 kWh	1.99E+01
	PERC bi-facial, ground mounted	M6	450	30	1573	1 kWh	1.93E+01
	PERC bi-facial, ground mounted	M12	500	30	1573	1 kWh	1.84E+01
Lunardi et al. 2018 [11]	PERC (EGS feedstock)	–		25	1700	1 kWh	2.60E+01
	PERC (SGS feedstock)	–		25	1700	1 kWh	1.99E+01
	PERC	–		25	1700	1 kWh	1.98E+01
	(UMG-Si feedstock)						
Luo et al. 2018 [12]	PERC mono-facial, roof-integrated	M2	244	30	1580	1 module	2.19E+05
	PERC bi-facial, roof-integrated	M2	238	30	1580	1 module	1.99E+05
	PERC mono-facial, roof-integrated	M2	244	30	1580	1 kWh	2.92E+01
	PERC bi-facial, roof-integrated	M2	238	30	1580	1 kWh	2.09E+01
This study	PERC mono-facial utility-scale	M12	460	30	1819	1 kWh	1.74E+01
	PERC mono-facial rooftop	M12	460	30	1819	1 kWh	2.17E+01

**Fig. 12.** Comparison among the greenhouse gas emissions generated from the electricity production by PV plant located in Catania, natural gas power plant, wind turbine and European electricity mix (these latter modelled according to the Ecoinvent database v3.8). The data are referred to 1 kWh produced.

Furthermore, the sensitivity analysis highlights the correlation between the energy production and environmental impacts: an increase of the energy yield leads to an increase of the environmental performances. Between the two sites analyzed, Catania in South of Italy and Piacenza in North of Italy, the first one has better environmental performances thanks to the higher GHI and consequently the higher electricity production. This was found to be valid for both roof-mounted and ground-mounted installations.

In conclusion, the study demonstrates that the adoption of PV plant instead of fossil fuel allowing an effective GHG emissions reduction further increased by relocating module supply-chain in countries with a more greener electricity mix.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution statement

Conceptualization and methodology: Elisabetta Brivio, Andrea Danelli and Pierpaolo Girardi; Investigation: Elisabetta Brivio, Andrea Danelli; Data curation: all authors; Writing—original draft preparation: Elisabetta Brivio, Andrea Danelli and Pierpaolo Girardi; Writing—review and editing: all authors; Supervision, Pierpaolo Girardi. All authors have read and agreed to the published version of the manuscript.

Supplementary material

Table S1. Inventory for the inverter adopted in the rooftop PV plant.

Table S2. Inventory for the printed wiring board of the Sunterno inverter.

Table S3. Inventory of the utility-scale inverter.

Table S4. Inventory of the cell PERC.

Table S5. Inventory of PERC module production with an area of 2.17 m² and an efficiency of 21.16%.

Table S6. Potential environmental impacts generated by the production of 1 PERC module according to the three scenarios.

The Supplementary material is available at <https://www.epj-pv.org/10.1051/epjpv/2024005/olm>.

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