Technology Collaboration Programme
by iea

International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability – Environmental LCA of PERC Technology

PVPS

Environmental Life Cycle Assessment of Passivated Emitter and Rear Contact (PERC) Photovoltaic Module Technology

2024

Report IEA-PVPS T12-26 : 2024

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme comprises 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (PVPS) is a TCP within the IEA; it was established in 1993. The mission of the programme is to “enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.” To achieve this, the programme’s participants have undertaken a variety of joint research projects in photovoltaic power systems applications. The overall programme is headed by an executive committee comprising one delegate from each country or organisation member, which designates distinct tasks, which may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, SolarPower Europe, the Smart Electric Power Alliance, the Solar Energy Industries Association, and the Copper Alliance are also members.

Visit us at: www.iea-pvps.org.

What is IEA PVPS Task 12?

Task 12 aims at fostering international collaboration in safety and sustainability that is crucial for assuring PV grows to levels making it a major contribution to the needs of the member countries and the world. The overall objectives of Task 12 are to 1. quantify the environmental profile of PV in comparison to other energy technologies, 2. investigate circularity options for PV systems as deployment increases and older systems are decommissioned, and 3. define and address environmental health and safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy, material, and emission flows in all the stages of the PV life cycle. The second objective is addressed through analysis of strategies including recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest. Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and TotalEnergies. Support from the U.S. Department of Energy and TotalEnergies are gratefully acknowledged.

Further information on the activities and results of the task can be found here.

Authors

- **Main Content:** A. Danelli, E. Brivio, P. Girardi, N. Baggio, J. Libal
- **Editor:** A. Danelli

COVER PICTURE

PERC module, courtesy of FuturaSun, Italy

ISBN 978-3-907281-47-5: Environmental Life Cycle Assessment of Passivated Emitter and Rear Contact (PERC) Photovoltaic Module Technology

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS
Task 12
PV Sustainability

Environmental Life Cycle Assessment of Passivated Emitter and Rear Contact (PERC) Photovoltaic Module Technology

Report IEA PVPS T12-26:2024
March 2024

ISBN 978-3-907281-47-5

TABLE OF CONTENTS

Table of Contents 6

Acknowlegments 7

List of abbreviations 8

Executive summary 10

1. Introduction 11

2. Goal and scope definition 13

- 2.1. Methodology 13
- 2.2. Impact categories 14
- 2.3. Photovoltaic plant description 15

3. Life Cycle Inventory 17

- 3.1. Silicon supply chain 17
- 3.2. Photovoltaic PERC cell production 17
- 3.3. PERC module production 20
- 3.4. LCI of the balance of system 23

4. Impact Assessment 26

- 4.1. Results in the different scenarios and configurations 26
- 4.2. Sensitivity analysis: influence of the service lifetime 28
- 4.3. Contribution analysis 31
- 4.4. Comparison with Al-BSF technology 32

5. Conclusions 35

6. References 37

Annex 1 – Life Cycle Impact Assessment 40

Annex 2 – FuturaSun SilkPro module data sheet 44

ACKNOWLEGMENTS

This report received valuable contributions from several IEA PVPS Task 12 members and other international experts. Many thanks to: Rolf Frischknecht, Mariska de Wild-Scholten and Garvin Heath for their valuable comments in improving this work.

This work has been financed by the Research Fund for the Italian Electrical System under the contract agreement between RSE S.p.A. and the Ministry of Economic Development - General Directorate for the Electricity Market, Renewable Energy and Energy Efficiency, Nuclear Energy in compliance with the Decree of April 16, 2018, and has received funding from the European Commission’s Horizon 2020 research and innovation programme under grant agreement Nº 792059 (project GOPV).

LIST OF ABBREVIATIONS

AE	accumulated exceedance
ADP	abiotic depletion potential
Al-BSF	aluminium back surface field
CN	China
CT	Catania
DE	Germany
EGS	electronic grade silicon
Eq	Equivalent
FU	functional unit
GHI	global horizontal irradiance
GLO	Global
GOPV	Global Optimization of Integrated Photovoltaic System for Low Electricity Cost (Horizon-2020 project)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISC Konstanz	International Solar Energy Research Center Konstanz
ISO	International Organization for Standardization
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
NMVOC	Non-methane volatile organic compound
ODP	ozone depletion potential
PBA	Printed board assembly
PC	Piacenza
PEF	Product Environmental Footprint
PERC	passivated emitter and rear contact
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
RER	Europe
RoW	rest of world
SG	solar grade

SGS	solar grade silicon
tkm	tonkilometer (unit for transport services)
UMG-Si	upgraded metallurgical silicon
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

The photovoltaic (PV) sector has undergone major expansions and evolutions during the last years, and the technologies that are currently marketed are numerous and very different. For Italy's energy sector, which aims to be sustainable from the environmental and economic perspective, it is important to evaluate and compare the environmental profile of the various PV generation technologies. Among high-efficiency technologies, the passivated emitter and rear cell (PERC) technology holds the largest market share. PERC modules are mostly made with half-cut monocrystalline silicon cells which allow an increase in the energy output of solar panels: by cutting the cells in half, their current is likewise cut in half, lowering resistive losses and allowing the solar cells to produce more electricity. Furthermore, using half-cut cells, the panel has more cells than regular panels, consequently the panel is divided in half so that the top and bottom halves act as two independent panels, producing electricity even if one half is shaded. In addition, the PERC cells are characterised by a rear surface passivation stack with lower surface recombination velocities and parasitic absorption than the back surface field layer in Al-BSF device. In this way, it is possible to increase the internal reflection, converting more solar energy into electricity, as compared to a monocrystalline silicon technology like aluminium back surface field technology (Al-BSF).

This report investigates the potential environmental impacts associated with PERC technology using a life cycle assessment (LCA) approach and compares them with those related to monocrystalline silicon technology (Al-BSF). At present, the number of published LCA studies related to PERC technology is small; they mostly use inventory data from the literature and are not tailored to the Italian context for the considered level of solar radiation. This LCA work helps to fill this gap by investigating a hypothetical 84.7 MW_p power plant with PERC modules. A notable differentiating feature of this LCA is that it is based on primary data collected from the PERC cell manufacturer as well as primary data from manufacturing of the inverter and single-axis tracker. Two possible designs are analysed: (1) modules mounted on a single-axis solar tracker and (2) modules installed on a fixed structure. In addition, two possible PV plant sites with different irradiance levels are considered: one in the north of Italy and the other in the south of Italy.

For the analysed configurations, in the case of the PV plant installed in the south of Italy (with an annual irradiation of about 1,820 kWh/ m^2/y), the estimated greenhouse gas emissions are 17.1 g CO_2 eq. /kWh if the PV plant is equipped with mono-axial solar trackers and 20.7 g CO_2 eq. /kWh if the modules are at fixed angle (34°). The obtained values are comparable but slightly lower (approximately -15%) than those estimated for conventional aluminium back surface field technology. Since data came from a specific manufacturer, it is not easy to understand whether advantages are due to technology gain or to specific more efficient processes. Finally, the results for the two installation sites (with the same PV system configurations) reveal, as expected, that the value of the incident solar radiation plays a crucial role in the systems' environmental performance, leading to lower potential environmental impacts per kWh electricity produced for sites with the highest solar irradiation levels.

1.INTRODUCTION

In 2022, solar PV generation increased by a record 270 TWh (+26%) worldwide, reaching almost 1,200 TWh [1]. In Europe, PV market grow again in 2022, with 41.5 GW installed, led by Spain (8.1 GW), Germany (7.5 GW), Poland (4.9 GW) and the Netherlands (3.9 GW) [2]. This exceptional growth is due to the fact that solar energy is seen as a key factor for meeting increasing worldwide electricity demand while reducing greenhouse gas emissions [3]. PV growth has been pushed by strong policy support. In Italy, for example, the National Energy and Climate Plan foresees the cumulative installed PV capacity of 52 GW in 2030, with an annual electricity production of 73 TWh [4]; this means that at least 3 GWh/year should be installed in Italy within this decade (Figure 1).

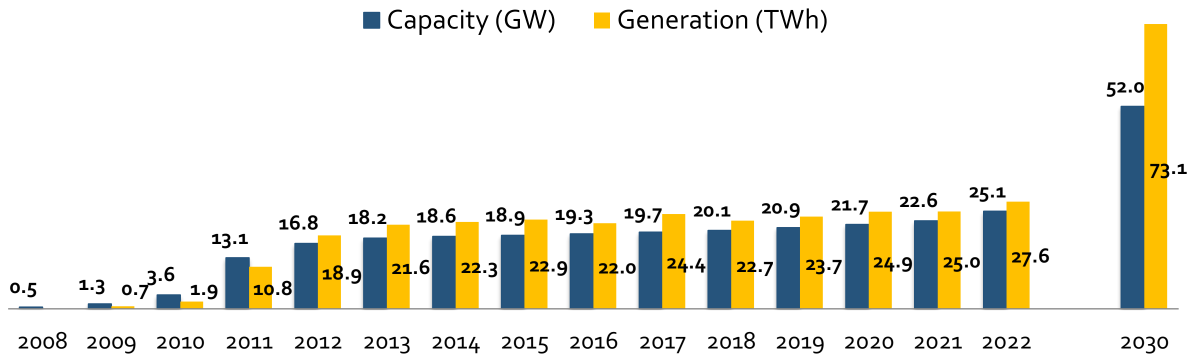


Figure 1: Growth trend for the PV sector in Italy and the target for 2030.

To further reduce costs and decrease greenhouse gas emissions, however, PV systems are expected to further increase their efficiency and their lifetime [5]. In this framework, the Passivated Emitter and Rear Cell (PERC) solar cell has been established as the most competitive crystalline-silicon technology in use as of recent years. In fact, PERC has become the standard technology type amongst many module manufacturers, superseding older cell structures such as aluminium Back Surface Field (Al-BSF) [6] (Figure 2

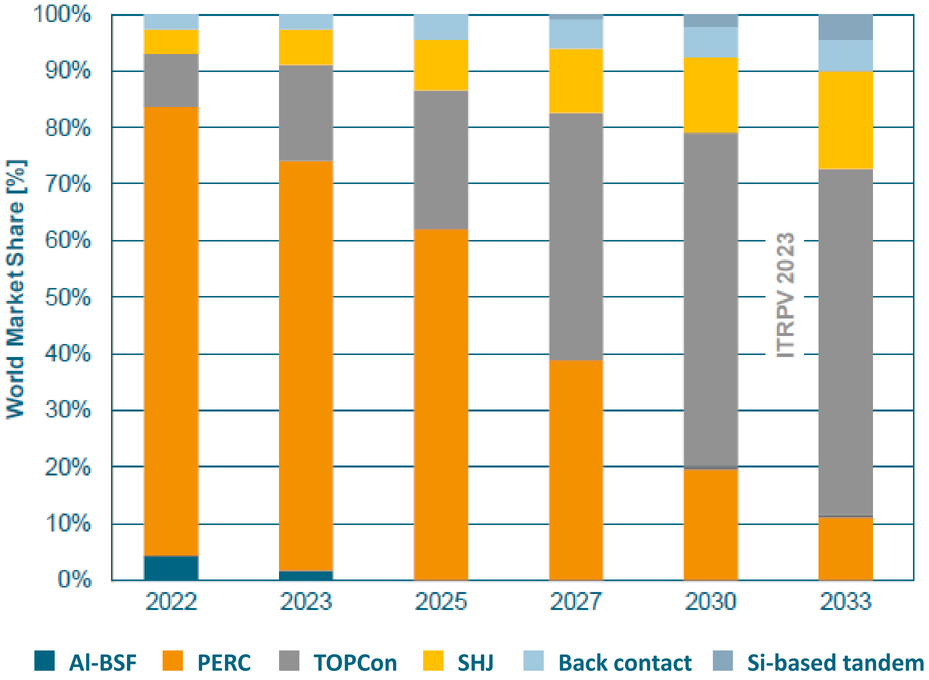


Figure 2). A PERC cell is a modified silicon cell that has an additional dielectric passivation stack on the rear of the cell to achieve increased energy conversion efficiency.

For an effective transition towards a sustainable energy sector, not only should the direct emissions of greenhouse gases during the generation of electricity be tracked, but also all the direct and indirect emissions associated with construction, upstream supply chain processes, and decommissioning. Moreover, the complete range of possible environmental life cycle impacts should be considered [7]. A good, standardised method to reach this goal is to perform a life cycle assessment (LCA) [5] in accordance with International Organization for Standardization (ISO) 14040 [8] and ISO 14044 [9] and in the case of photovoltaics also to "Methodology Guidelines on Life Cycle Assessment of Photovoltaic" by the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) [10].

In this framework, the current report presents the LCA of utility-scale installations solutions based on PERC technology. Two possible plant configurations are analysed: ground-mounted on a mono-axial tracker and ground-mounted on a fixed structure. To assess the influence of the incident solar radiation value on the LCA results, two possible locations are considered: in the north of Italy (Piacenza) and in the south of Italy (Catania). Finally, the LCA results obtained for the PERC technology are compared with those associated with the aluminium back surface field (Al-BSF) technology, estimated for the same plant configurations and locations. Aluminium BSF cell technology remains the most prevalent technology in LCA databases even if many expect it to be largely phased out by the end of 2023 (Figure 2).

Compared to other studies based on secondary data, we were able to work closely with the manufacturers of cells, modules, inverters, trackers, and PV system operators; therefore, the resulting LCA is based on primary data (discussed in Chapter 3), rather than only literature information.

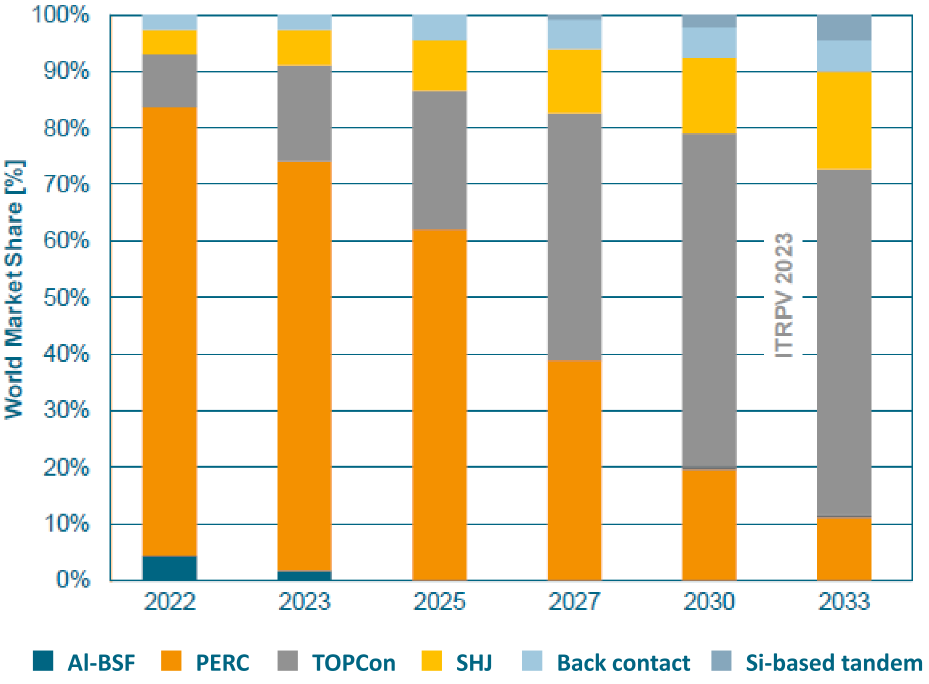


Figure 2: Market shares of different cell technologies as reported in the *International Technology Roadmap for Photovoltaics 2023* [11] (ITRPV): aluminium Back Surface Field (Al-BSF), Passivated Emitter and Rear Cell (PERC), Tunnel Oxide Passivated Contact cell (TOPCon), Si-Heterojunction (SHJ), back contact, Si-based tandem.

2. GOAL AND SCOPE DEFINITION

The main goal of this study is the assessment of the potential environmental impacts related to electricity generation by high-efficiency PV PERC technology based on half-cut cell. The study aims to evaluate the environmental impacts at the PV plant level, considering its entire life cycle (from realisation to dismantling), and, above all, to highlight the components and processes mainly contributing to environmental impacts, such as climate change or abiotic resource depletion.

Specifically, the current report illustrates the life cycle impact assessment (LCIA) of an 84.73 MWDC[1] ground-mounted PV plant equipped with PERC modules. The ground-mounted PV systems are characterised by a competitive levelized cost of energy and higher energy production in terms of specific yield (kWh/kW_p).

This study considers two different PV plant configurations: the first with modules mounted on a mono-axial solar tracker and the second with modules at a fixed tilt. The use of trackers allows for increased energy production from a PV plant; on the other hand, however, manufacturing the trackers requires more raw materials and energy than those needed for fixed mounting systems. The influence of the irradiation levels, derived from the PVGIS database [12], on the LCIA was explored by selecting two different sites: one in the north of Italy (Piacenza) and one in the south of Italy (Catania).

The lifetime of the system, which is a relevant parameter in PV LCAs [5], is set to 25 years, which corresponds to the duration of the performance warranty that most module producers provide; additionally, the effect of a 5-year extension of the plant lifetime on the environmental impacts per kWh produced is evaluated.

Finally, to understand the differences of using high-efficiency PV technologies, such as PERC, instead of traditional ones, this study compares the environmental impacts (per kWh produced) of PERC to the more widely installed monocrystalline silicon technologies (i.e., Al-BSF).

2.1. Methodology

A life cycle approach, applied as defined by ISO 14040 [8] and ISO 14044 [9], was used to model a PV system based on PERC technology. Because the ISO standards provide only the general framework for LCA, leaving the individual practitioner with a range of choices that can influence the results and thus the conclusions of an LCA study, the recommendations from the “Methodology Guidelines on Life Cycle Assessment of Photovoltaic” by the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) [10], were followed (with some exception discussed below).

The attributional approach [13], which is the most prevalent type of LCA published [7], was adopted.

The functional unit (FU), which represents the unit to which all inputs and outputs of the studied system refer, was chosen to be 1 kWh of AC electricity measured at the busbar of the PV plant. The metric is therefore defined as the total life cycle environmental impacts of the PV plant divided by its net amount of electricity delivered to the grid throughout its lifetime. The lower the metric value is, the more favourable it is for the environment, or the more benefit is generated for the same environmental impacts caused. The adoption of this FU allows for comparisons among PV technologies and electricity-generating technologies in general. The current LCA study was carried out using the SimaPro software, release 9.3.0.3, and the Ecoinvent database, version 3.8 (cut-off approach).

---

[1] Corresponding to 70.6 MW_{AC}

2.2. Impact categories

The potential environmental impacts were evaluated using the midpoint indicators of the Product Environmental Footprint[2] Category Rules, as suggested by IEA PVPS guidelines [10]. The only exception is the ionizing radiation category, which is omitted because it is not relevant for the system investigated. The considered impact categories and indicators are listed in **Error! Reference source not found.**. However, the results for all impact categories suggested by IEA PVPS guidelines are given in Annex 1 – Life Cycle Impact Assessment.

Table 1: List of impact categories addressed in this PV LCA study along with their indicator, unit, and source.

Impact category	Indicator	Unit	LCIA method	Robustness[3]
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC [14]	I
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 eq	Steady-state ODPs 1999 as in WMO assessment [15]	I
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	[16] as applied in ReCiPe	II
Respiratory inorganics	Impact on human health	Disease incidence	PM method recommended by UNEP [17]	I
Acidification	Accumulated exceedance (AE)	mol H+ eq	Accumulated exceedance [18], [19]	II
Freshwater eutrophication	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model [20] as implemented in ReCiPe [17]	II
Marine eutrophication	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model [20] as implemented in ReCiPe [17]	II
Terrestrial eutrophication	Accumulated exceedance (AE)	mol N eq	Accumulated exceedance [18], [19]	II
Land use	Soil quality index[1]	Dimensionless (Pt)	Soil quality index based on LANCA model	III
Resource use, energy carriers	Abiotic resource depletion—fossil fuels (ADP-fossil)	MJ	CML 2002 [21] and [22]	III
Resource use, mineral and metals	Abiotic resource depletion (ADP-ultimate reserves)	kg Sb eq	CML 2002 [21] and [22]	III

---

[2] EF 3.0 method (adapted for SimaPro substances), v1.03.

[3] According to ILCD levels [36]: "Level I" (recommended and satisfactory), "Level II" (recommended but in improvements), "Level III" (recommended, but to be applied with caution).

2.3 Photovoltaic plant description

The LCA study considered a hypothetical PV plant with a peak power of 84.73 MW_{DC} that uses monocrystalline modules with 144 half-cut cells. For the boundaries of the analysed system, the modules, the trackers, and the inverters were considered (Figure 3). The connections to the network and the electrical substation were excluded from the analysis, as their realization may change case by case. The construction phases, the operation of the plant, and its dismantling (only the end of life of the modules[4]) were included in the assessment. This means that the study accounted for the inputs of raw materials and their supply chains, the energy supply, the manufacturing of panels, the mounting systems, the cables, the inverters, and all other components needed to produce electricity [3]. To deal with the operating phase, we considered the replacement of the inverters after 17 years and the substitution of the tracker actuators and control boards based on the probability of failure. Only the installation of the tracker and the mounting system (for which primary data from the manufacturer were available) were included in the *in-situ* construction phase. The system boundaries adopted in this LCA study are outlined in Figure 3.

The analysed PV plant includes 184,196 mono-facial modules characterised by a nominal power of 460 Wp (21.16% of efficiency) and an area of 2.17 m^2, 7,085 trackers realised in low alloy weathering steel (26 modules each, 13 x 2 portrait) and 426 inverters with a nominal power of 166 kW (replaced after 17 years). In the operating phase of the PV plant, it is supposed that 1,772 actuators and 709 control boards of the tracker are replaced due to failures. Table 2 lists the different scenarios evaluated in this LCA study. We note that the Al-BSF technology requires a higher surface area of modules than the PERC technology due to lower efficiency [10] (19.5% module efficiency compared to 21.16%).

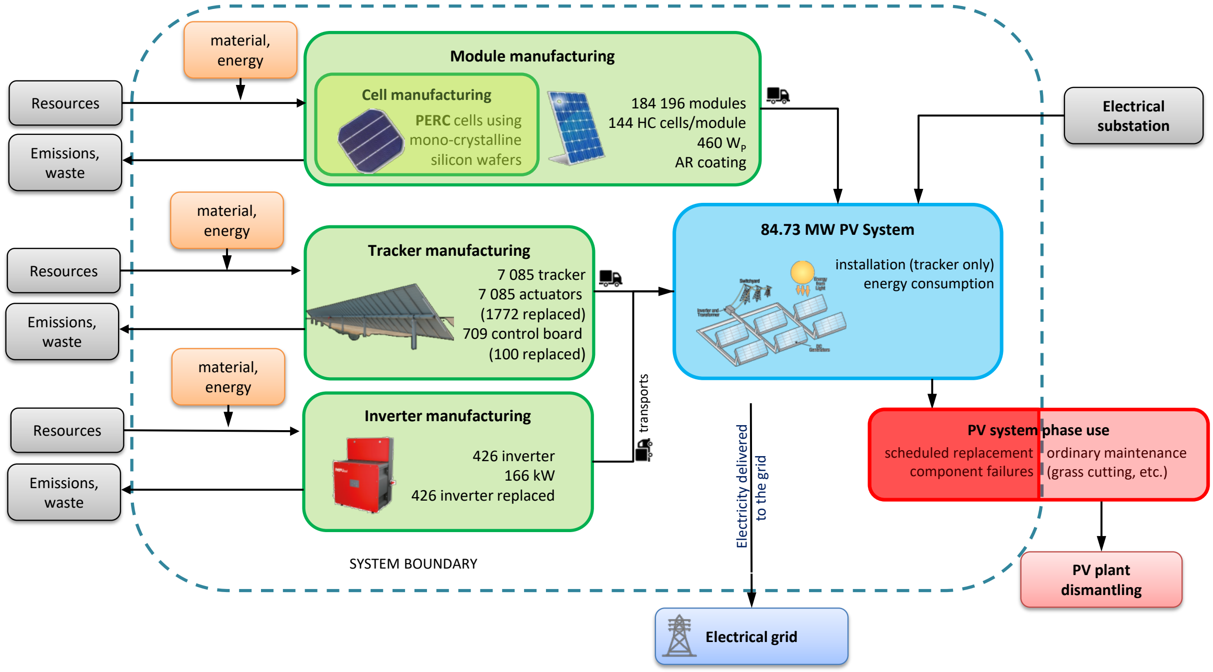


Figure 3: Outline of system boundary with the unit processes included in the LCA study.

---

[4] Life cycle inventories of PV module end-of-life have been taken from [24], according to which, "due to limited waste volumes, c-Si PV modules are mainly treated in recycling plants designed for treatment of laminated glass, metals or electronic waste. Only the bulk materials (glass, aluminium, and copper) are recovered, while the cells and other materials such as plastics are incinerated".

The amount of electricity produced throughout the lifetime of the analysed PV plant configurations considerably affects the LCA results. Core data for the assessment of this crucial parameter are both the annual irradiation (i.e., global horizontal irradiance [GHI]) at the installation site and the technical features of the PV system, such as the inverter and module efficiency rate as well as the mounting and supporting structures of the modules [23] together with orientation and tilt angle. The electricity production was determined by starting from the data related to the geographic coordinates of the installation and by considering the adopted PV technology and the mounting system. For the PERC technology, we assumed the degradation rate declared by the module producer (as reported in the FuturaSun module datasheet, see Annex 2): 3% the first year, 0.4% from the second to the twenty

year, and 0.5% in the following years. For the Al-BSF technology, we considered a linear degradation of 0.7% per year [10].

Table 2: List of the PV plant configurations considered in the LCA study, including the PV technology, the location, the total module surface area required, the related Global Horizontal Irradiance (GHI), the amount of electricity produced during the plant's entire useful life (25 years), and the average annual yield.

Plant configuration	PV technology	Location	Capacity	Module area	Module efficiency	GHI	Production	Avg. yield
			MWp	m^2	%	$kWh/m^2/y$	GWh	$kWh/(kW_p·y)$
Modules on mono-axial solar tracker	PERC	Catania	84.73	4.00E+05	21.16%	1,819	4.44E+03	2,096
Modules at fixed tilt[5]	PERC	Catania	84.73	4.00E+05	21.16%	1,819	3.60E+03	1,700
Modules on mono-axial solar tracker	PERC	Piacenza	84.73	4.00E+05	21.16%	1,368	3.330E+03	1,572
Modules at fixed tilt[5]	PERC	Piacenza	84.73	4.00E+05	21.16%	1,368	2.89E+03	1,364
Modules on mono-axial solar tracker	Al-BSF	Catania	84.73	4.35E+05	19.50%	1,819	4.22E+03	1,992
Modules at fixed tilt[5]	Al-BSF	Catania	84.73	4.35E+05	19.50%	1,819	3.42E+03	1,615
Modules on mono-axial solar tracker	Al-BSF	Piacenza	84.73	4.35E+05	19.50%	1,368	3.16E+03	1,492
Modules at fixed tilt[5]	Al-BSF	Piacenza	84.73	4.35E+05	19.50%	1,368	2.76E+03	1,303

---

[5] Here and after the tilt angle is 34°

3. LIFE CYCLE INVENTORY

Primary data about PERC cell production and module assembly were used to carry out this study, while the first stages in the PV supply chain — from the production of metallurgical-grade silicon to silicon wafer production — were modelled using the data published by Frischknecht et al. in [24].

The life cycle inventory (LCI) of the inverter and the mono-axial solar tracker has been gathered through personal communications from manufacturers (see section 3.4) to the authors of this study in the framework of the European Union-funded project, Global Optimization of Integrated Photovoltaic System for Low Electricity Cost (GoPV) (https://doi.org/10.3030/792059).

3.1. Silicon supply chain

The supply chain of PV electricity production covers the polycrystalline silicon feedstock purification process (using the Siemens process), the crystallisation process (the Czochralski method in case of monocrystalline silicon ingot), wafering, cell processing, and module assembly, as shown in Figure 4.

Because we were not able to gather primary data regarding the first stages in the silicon supply chain, for the realisation of the polysilicon, the ingots and the wafer, we used the LCI data published in [24].

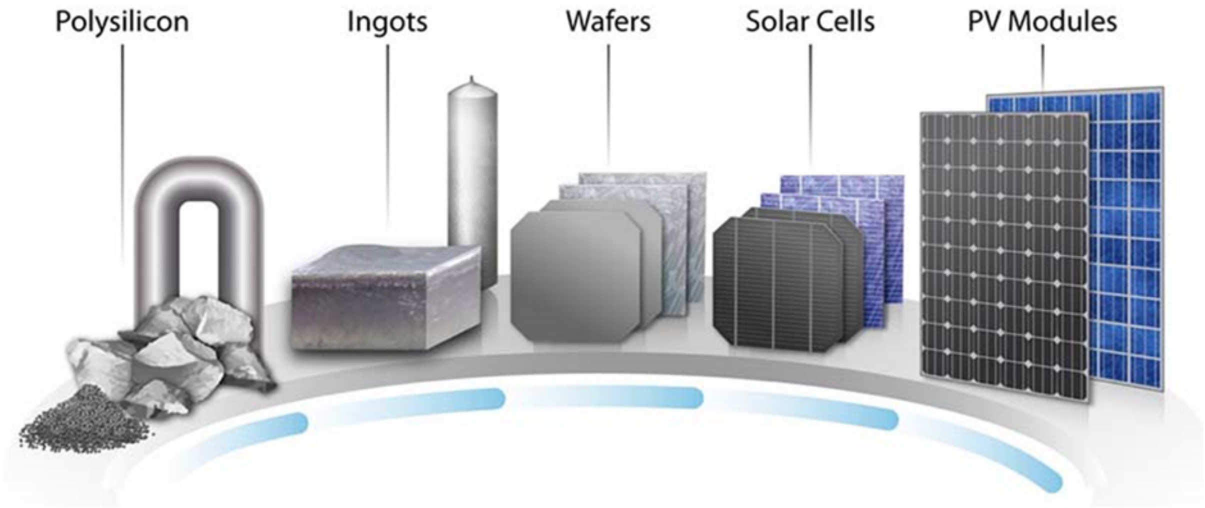


Figure 4: Supply chain of silicon-based PV electricity production [25].

3.2. Photovoltaic PERC cell production

The LCI data on material and energy consumption as well as on emissions were gathered through questionnaire, prepared by the research center RSE (Ricerca sul Sistema Energetico) , by the International Solar Energy Research Center Konstanz (ISC Konstanz, https://isc-konstanz.de/), whose business is the research and development of crystalline silicon solar cells, modules, and overall energy systems. ISC Konstanz has an industrial pilot line for the production and extensive characterisation of crystalline silicon (c-Si) solar cells and modules, and, among its various activities, it provides technology transfer of solar cell and module technologies. The scope of the services offered by ISC can vary greatly: from carrying out a small and tightly defined set of measurements, to developing an entire cell concept on behalf of and in close cooperation with the partner. The data submitted by ISC Konstanz to

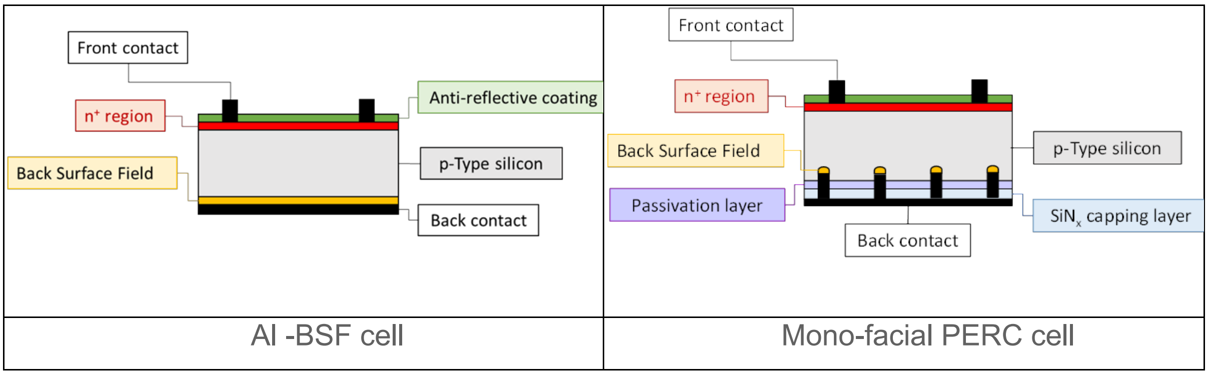
RSE are based on the quantitative information received by ISC (within the framework of such technology transfers/ramp-up support services) by the suppliers of industrial solar cell processing equipment. Starting from this quantitative information (facility utility matrix - FUM, data from 2022) of the single equipment, the yearly consumption of a 4.2 GW/year PERC solar cell factory has been calculated. This production process is assumed the same as that used to manufacture the solar cells purchased by FuturaSun.

Table 3 shows the unit process data of PV PERC cell production; the data refer to the manufacturing of mono-facial PERC cells with an efficiency of 22.5% in which an M12 wafer (size 210 mm x 210 mm) with a thickness of 170 µm is used. The electricity demand to produce a cell has been estimated by the ratio between the total annual consumption of the production lines (108,562.73 MWh) and the number of cells produced (424,300 thousand) in a year. The electricity energy consumption includes auxiliary systems such as HVAC system.

Half-cut cells are typical silicon solar cells that have been sliced in half by a laser cutter.

For the data on transport distance, PV cell factory and emissions to air, we assumed the values published in [24].

Note that compared to the LCI data on Al-BSF cells published in [24], the PV cells production processes seem to have significantly reduced the electricity demand (from 17.7 kWh/m^2 to 5.8 kWh/m^2) and metallization paste consumption (from more than 60 g/m^2 to 12 g/m^2). Unfortunately, authors are not able to state whether this reduction is due to the PERC technology or an optimization of the production process by the manufacturer. Figure 5 shows the schematic architecture of a standard Aluminium Back Surface Field (Al-BSF) cell and a mono-facial PERC cell.



Al -BSF cell

Mono-facial PERC cell

Figure 5: Structure of an Al-BSF cell and mono-facial PERC cell [26]**.**

Table 3: LCI data of Mono-PERC solar cell production. These LCI data were obtained from ISC Konstanz.

	Name	Location	Unit	Amount	Remarks
Product	Mono-PERC cell	CN	m^2	1.00E+00	
Wafer	Single-Si wafer (phosphorus doped)	CN	m^2	1.04E+00	170-micron
Materials	Ag paste front side	GLO	mg	4.08E+03	100% Ag
	Ag paste rear side	GLO	mg	1.13E+03	100% Ag
	Al paste rear side	GLO	mg	6.80E+03	
Liquids	Deionised water	GLO	kg	2.87E+01	
	Additive[1]	GLO	kg	1.31E-02	
	Hydrochloric acid in 37% solution state	GLO	kg	1.41E-02	
	Sulfuric acid	RoW	kg	5.88E-02	
	Nitric acid in 67% solution state	RoW	kg	8.67E-02	
	Phosphorus oxychloride	RoW	kg	1.81E-04	
	Trimethyl-aluminium (TMA)	GLO	kg	2.42E-04	
	Potassium hydroxide in 40% solution state	GLO	kg	5.16E-02	
	Hydrogen fluoride in 49% solution state	GLO	kg	8.02E-02	
	Hydrogen peroxide in 30% solution state	GLO	kg	1.20E-02	
Gases	Nitrogen 6.0	GLO	kg	3.40E-09	Ultrapure gas
	Nitrogen 5.0	GLO	kg	3.23E-08	High-purity gas
	Silicon tetrahydride	GLO	kg	2.29E-03	
	Ammonia	RoW	kg	1.27E-02	
	Oxygen	RER	kg	3.15E-09	
	Dinitrogen oxide	RoW	kg	1.71E-05	
	Methane	GLO	kg	1.11E-03	
Energy	Electricity (consumption of auxiliary services included)	CN	kWh	5.80E+00	
Infrastructure	PV cell factory	GLO	unit	4.00E-07	
Utilities	Compressed dry air	RoW	m^3	1.13E+00	
	Cooling water	RER	m^3	2.32E-01	
Transport	Freight train	GLO	tkm	1.26E+00	
	Freight lorry	GLO	tkm	2.26E-01	
Disposal	Treatment, PV cell production effluent, to wastewater treatment, Class 3	GLO	m^3	3.96E-02	
	Disposal, waste, silicon wafer production, inorg, 9.4% water, to residual material landfill	GLO	kg	2.32E+00	
	Disposal, solvents mixture, 16.5% water, to hazardous waste incineration	GLO	kg	1.72E-01	
Emission to air	Water		kg	3.96E+00	
	Hydrogen fluoride		kg	3.04E-02	
	Silicon		kg	3.16E-08	
	Silver		kg	6.64E-06	
	Ammonia		kg	3.07E-05	
	Chlorine		kg	2.48E-03	
	Hydrogen		kg	1.10E-02	
	Silicon		kg	2.62E-03	
	NMVOC		kg	1.26E-02	

1. Approximated with isopropanol, in accordance with [24].

3.3. PERC module production

The primary data on the production of a PV module based on PERC technology (Figure 6) were gathered from FuturaSun (https://www.futurasun.com/en/), an Italian company with production plants in Asia (production capacity of 1.2 GW/year), which specializes in the production of high-performance PV modules.

Table 4 shows the main characteristics of a 460-W PERC module produced by FuturaSun, with an area of 2.17 m^2 (2,094 mm x 1,038 mm) and an efficiency of 21.16%, and Table 5 shows the unit process data.

The module is made by assembling 144 half-cut M6 cells (166 mm x 83 mm), with an area of 137.78 cm^2. Since the primary data used in the LCI for cells refer to an M12 (210 mm x 210 mm) PERC cell (see Subchapter 3.2), the life cycle inventory (LCI) of the production of 72 M6 cells is assumed to be equivalent to the LCI of producing 45 M12 cells for the purpose of this study (because the cells' thickness is the same, it can be assumed that the LCI is proportional to the cells' surface where the FU is 1 m^2 of the cell).

Regarding transportation, this study considers the transportation directly involved in the production process (i.e., 600 km by train and 100 km by truck as reported in [24]), as reported in Table 5

Table 5, and those used to import the modules from China to Europe (Table 6). For the latter, according to the IEA report on *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems* [24], we assumed a travel distance from China to Europe of 19,994 km by transoceanic ship, plus 943 km by truck (Table 6).

No direct emissions to air have been declared by the manufacturer.

Figure 6: Picture of FU 460 M Silk Pro module and its use in a utility scale pant (courtesy of Futurasun).

Table 4: Key characteristics of a FuturaSun mono-facial PERC module.

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:	2,094 x 1,038 x 35 mm
Weight:	23.6 kg
Module power (Pmax):	460 W
Module efficiency:	21.16%
Number of cells:	144 half-cut M6 cells
Performance guarantee:	25 years

Table 5: LCI data of PV mono-PERC module production, with an area of 2.17 m^2 and an efficiency of 21.16%. These LCI data were obtained from FuturaSun based on actual module manufacturing.

	Name	Location	Unit	Amount	Note
Product	460-W PERC module, at plant	CN	m^2	1	
Cells	PV PERC cell	CN	m^2	9.05E-01	144 half-cut M6 cells
Materials	Aluminium alloy, Al6063-T5	GLO	kg	1.19E+00	
	Aluminium working process	GLO	kg	1.19E+00	
	Solar glass (3.2 mm)	GLO	kg	7.63E+00	
	Copper	GLO	kg	7.45E-02	
	Lead	GLO	kg	6.75E-03	
	Tin	GLO	kg	1.01E-02	
	Ethylvinylacetate, foil	GLO	kg	9.87E-01	
	Polyvinylfluoride, film	GLO	kg	4.52E-02	
	Polyethylene terephthalat granulate	GLO	kg	3.11E-01	
	Silicone products	RoW	kg	1.14E-01	
	J-box + cables	GLO	kg	1.14E-01	
	Anti-reflex coating	GLO	m^2	9.92E-01	weight percentages: 13% tetraethyl ortho silicate,69.7% ethanol, 8.4% triethylene glycol, 8.9% hydrochloric acid. sintering and heating processes require an energy consumption of 2.3 kWh
Packaging material	Polystyrene	GLO	kg	2.10E-02	
	Cardboard	RoW	kg	2.44E-01	
	Pallet	RoW	kg	2.89E-01	
Energy	Electricity	CN	kWh	4.13E+00	
Utility	PV panel factory	GLO	unit	4.04E-06	
	Tap water from public supply	RoW	m^3	6.99E-04	
Transport	Freight train	RER	tkm	1.66E+00	
	Freight lorry	RER	tkm	2.77E+00	
Disposal	Waste, from silicon wafer production	GLO	kg	3.52E-03	
	Waste plastic, mixture	GLO	kg	4.37E-03	

Table 6: Transport from China to Europe for module import. The values refer to 1 m^2 of the module.

	Name	Location	Unit	Amount	Note
Product	PERC module, at regional storage	RER	m^2	1	
Transport	Freight lorry	RER	tkm	1.02E+01	
	Freight transoceanic ship	RER	tkm	2.17E+02	

Since the energy demand in the Silicon supply chain has a great influence on the Life Cycle Impact Assessment, especially on the *Climate Change* impact category, it is important to use up-to-date and accurate data in this regard. In the current study, the values of the energy consumption to produce a PERC cell and module come from a specific manufacturer; it is therefore relevant to compare them with other literature data. Table 7, which lists the energy consumption along the process chain as reported in different sources, shows that the values of energy demand for the cell and module manufacture used in this study are in line with the most recent publications.

Table 7: Overview of main energy consumption in the silicon supply chain according to various sources: Ecoinvent v.3.7 , IEA PVPS 2015 [27], **IEA PVPS 2020** [24], **Muller et al.** [28] **and this study.**

Stage of Si supply chain	Unit	Ecoinvent 3.7 (Al-BSF)	IEA PVPS 2015 (Al-BSF)	IEA PVPS 2020 (Al-BSF)	Muller et al. 2021 (PERC)	Current study (PERC)
MG-SI	kWh/kg	11	11	11	11	11[6]
Poly-Si	kWh/kg	110	110	49	72	49[6]
Cz-Si	kWh/kg	85.6	68.2	32	38.4	32[6]
Wafering	kWh/m^2	8	25.7	4.76	2.35	4.76[6]
Cell	kWh/m^2	30.2	14.4	17.7	6.24	5.8
Module	kWh/m^2	4.71	3.73	6 [29]	3.32	4.13

3.4. LCI of the balance of system

A notable contribution of this study is the publication of new, primary LCI data regarding the manufacture of the mono-axial solar tracker and inverter. These data were collected through interviews with a tracker and inverter manufacturer who were part of the GOPV project (https://doi.org/10.3030/792059) along with RSE (the project's objectives included carrying out LCA studies of photovoltaic components). In particular, the data about the solar tracker have been collected from Convert Italia SpA[7], an Italian company active in the design, production and sale of single-axis trackers for utility scale photovoltaic plants. All tracker structural parts are manufactured in the Convert Italia plants in Italy and Turkey. Over the last 2 years (period to which the collected data refer), Convert Italia has been producing trackers for an equivalent photovoltaic installed capacity of about 1.2 GW/year (i.e., approximately 90,000

---

[6] Data from IEA PVPS 2020 [23].

[7] Single shareholder of Convert Italia is Valmont Industries Inc.

trackers). Table 8 shows the LCI data of a five-pile solar tracker with a weight of 628 kg, to which 26 modules (portrait orientation) can be mounted. The actuator of the tracker implies an energy consumption of 10.95 kWh/year. The standard distance from the tracker manufacturing site to the installation site was assumed to be equal to 1,000 km, 500 by freight train and 500 km by lorry.

As for the inverter data, it was provided by a European manufacturer with which a confidentiality agreement was signed with RSE. Data collection, carried out by interview, took place in 2019. Table 9 shows the LCI data of a 166-kW inverter, with a weight of 100 kg, including materials and transport (1,000 km from the manufacturing site to the installation site). The inverter has a useful lifetime of 17 years.

Table 8: LCI data of a mono-axial solar tracker, with a weight of 628 kg (dimension 14 m x 4.2 m) to which 26 modules (portrait orientation) can be mounted. The data are shown per m^2 of module mounted (module dimension: 2,094 x 1,038 mm) on the tracker (FU 1) and also per single tracker (FU 2).

	Name	Location	Unit	FU 1 (1 m^2 of module mounted on the tracker)	FU 2 (1 tracker of size 14*4.2 m)	Note
Product	Solar tracker	RER	unit	1 m^2	1 tracker	
Materials	Weathering steel	RER	kg	1.09E+01	6.15E+02	In addition to the material, the metalworking processes must be included.
	Aluminium cast alloy	GLO	kg	8.86E-02	5.00E+00	
	Printed wiring board (surface mounted)	GLO	kg	9.76E-04*	5.50E-02*	A single control board (0.5 kg) leads the actuators of 10 solar trackers. Failure probability is 0.4% per year
	Electric motor	RER	kg	1.06E-01**	7.50E+00**	The weight of the actuator is 6 kg. Failure probability is 1% per year
	Copper cables	GLO	kg	3.54E-02	2.00E+00	
Transport	Freight train	RER	tkm	5.57E+00	3.14E+02	
	Freight lorry	RER	tkm	5.57E+00	3.14E+02	
Installation phase	Diesel	RER	kg	6.68E-01	3.77E+01	Fuel consumption to drive poles into the ground

* The value also includes the printed wiring board replaced during the tracker life span, 25 years. ** The value also includes the actuators replaced during the tracker life span, 25 years.

Table 9: LCI data of a 166-kW inverter, with a weight of 100 kg. The data refer to 1 kW.

	Name	Location	Unit	Amount	Note
Product	166-kW inverter	RER	kW	1	
Materials	Printed wiring board, surface mounted	CN	kg	5.42E-02	
	Aluminium	GLO	kg	1.20E-01	Inverter housing
	Inductors	GLO	kg	2.41E-01	60% copper
	Epoxy potting	RER	kg	4.82E-02	
	Aluminium, Heat sink	RER	kg	9.04E-02	100% in aluminium
	Cables	GLO	kg	2.41E-02	
	Switches	GLO	kg	1.20E-02	
	Electric connector	GLO	kg	1.20E-02	
Energy	Electricity	DE	kWh	1.20E-01	
Transport	Freight train	RER	tkm	3.01E-01	
	Freight lorry	RER	tkm	3.01E-01	

4. IMPACT ASSESSMENT

This section shows the potential environmental impacts associated with the production of 1 kWh (net) of AC electricity generated by the PERC PV plant. In addition, the results are compared with the impacts generated by the PV plant based on standard Al-BSF technology modelled according to the IEA report on *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems* [24].

4.1. Results in the different scenarios and configurations

The results of the impact assessment, evaluated according to Product Environmental Footprint (PEF) guidelines [30], referred to the FU (1 kWh) are reported in Table 10. Figure 7 shows, for each impact category, the result of each PV system configuration (i.e., PC 25 tracker; PC 25 fixed tilt; CT 25 tracker; CT 25 fixed tilt)[8] expressed as percentages of the highest value (set equal to 100%). The outcomes reveal that the CT 25 tracker solution (i.e., the PV plant located in Catania in which the modules are mounted on a mono-axial solar tracker) causes the lowest potential environmental impacts in all the impact categories (-17% compared to the CT 25 fixed tilt and -25% compared to the PC 25 tracker in the *Climate change* category). This means that the reduction in specific impacts from increased electricity production, which are obtained by using a tracker, exceeds the increase in impacts due to greater demand for raw materials (especially the precious metals used in the electronic components), the increased energy consumption for its production, and the increased material and energy consumption during operation and installation compared to the fixed structure. In [2]addition, the considered tracker, made solely with weathering steel, with almost no use of aluminium, is characterised by lower environmental impacts than those of traditional support structures.

The comparison between the same technology installed in southern and northern Italy, respectively (i.e., the fixed tilt PV plant located in Catania and Piacenza), shows that the solar radiation strongly affects the results[9]. The higher the radiation (CT = 1,819 kWh/m^2 and PC = 1,368 kWh/m^2), the higher the electricity production, with a consequent reduction in specific potential environmental impacts per kWh produced.

---

[8] Where CT stands for Catania, south Italy, and PC stands for Piacenza, north Italy, while 25 indicates the lifetime of plants in years.

[9] The influence on the solar radiation on the results is more evident with the use of tracker.

Table 10: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh). Comparison of the potential environmental impacts associated with the four PV plant configurations: PC 25 tracker (PV plant located in Piacenza with tracker and useful life of 25 years); PC 25 fixed tilt (PV plant located in Piacenza with fixed mounting system and useful life of 25 years); CT 25 tracker (PV plant located in Catania with tracker and useful life of 25 years); CT 25 fixed tilt (PV plant located in Catania with fixed mounting system and useful life of 25 years).

Impact category	PC		CT	
	25 tracker	25 fixed tilt	25 tracker	25 fixed tilt
Climate change (kg CO2 eq.)	2.28E-02	2.57E-02	1.71E-02	2.07E-02
Ozone depletion (kg CF11 eq.)	1.99E-09	2.25E-09	1.50E-09	1.81E-09
Photochemical ozone formation (kg NMVOC eq.)	8.75E-05	9.78E-05	6.57E-05	7.86E-05
Respiratory inorganics (disease inc.)	1.50E-09	1.68E-09	1.12E-09	1.35E-09
Acidification (mol H+ eq.)	1.40E-04	1.54E-04	1.05E-04	1.24E-04
Freshwater eutrophication (kg P eq.)	9.07E-06	9.88E-06	6.81E-06	7.94E-06
Marine eutrophication (kg N eq.)	3.64E-05	4.04E-05	2.73E-05	3.25E-05
Terrestrial eutrophication (mol N eq.)	2.99E-04	3.36E-04	2.25E-04	2.70E-04
Land use (Pt)	4.33E-01	4.94E-01	3.25E-01	3.98E-01
Resource use, energy carriers (MJ)	2.77E-01	3.12E-01	2.08E-01	2.51E-01
Resource use, mineral and metals (kg Sb eq.)	1.07E-06	1.16E-06	8.04E-07	9.33E-07

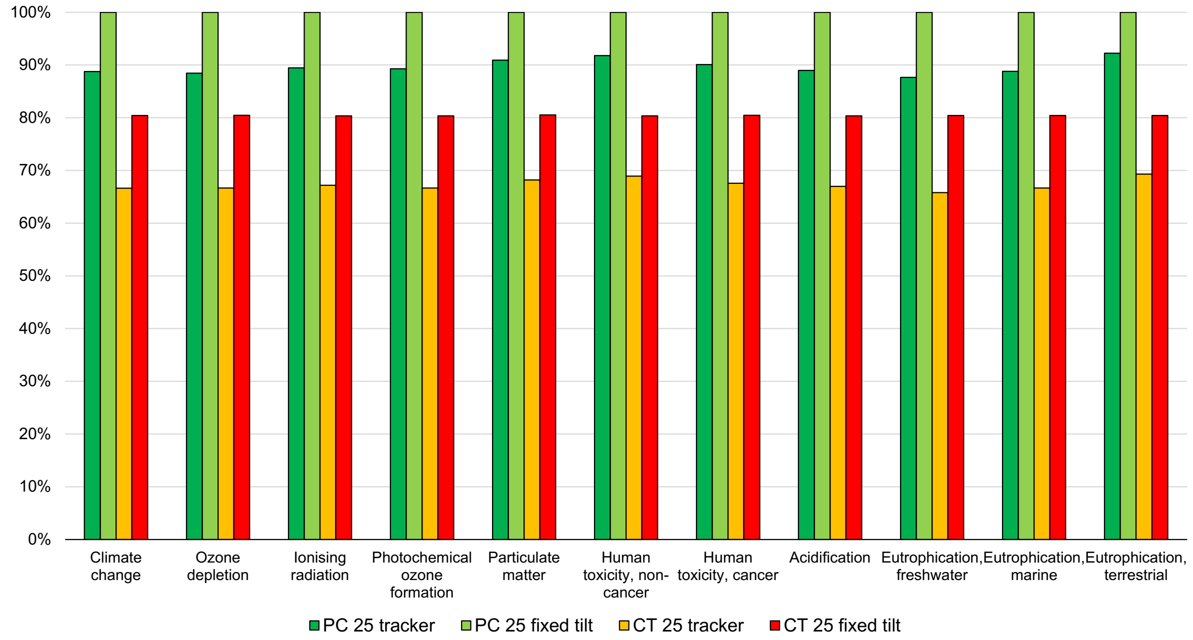


Figure 7: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh). Comparison of the potential environmental impacts associated with the four PV plant configurations. The worst solution is set equal to 100%.

4.2. Sensitivity analysis: influence of the service lifetime

To better understand the influence of the PV plant useful life on the environmental impacts, a sensitivity analysis was performed. More specifically, the base case, in which the plant lifetime is 25 years according to the performance warranty, is compared with a PV plant with a lifetime of 30 years (Table 11). The extension of the PV plant lifetime of 5 years, which implies an increase of the components substituted (for ordinary maintenance) and of the electricity produced during the entire lifetime of the system, leads to a reduction of the specific potential environmental burdens (-16% in all categories), as shown in Figure 8. The only exception is the *Land use* category, in which the impact variation is negligible.

The results obtained can be explained by considering that:

- inverters are replaced after 17 years;
- the failure probability of the tracker actuators (1 %/year) was assumed to be constant over time;
- the failure probability of the tracker electronic components (0.4 %/year) was assumed to be constant over time;
- as far as PV modules, after the 20th year of the plant's life, an annual degradation of 0.5% was considered.

Table 11: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh). Comparison of the potential environmental impacts associated with the four PV plant configurations: PC 30 tracker (PV plant located in Piacenza with tracker and useful life of 30 years); PC 30 fixed tilt (PV plant located in Piacenza with fixed mounting system and useful life of 30 years); CT 30 tracker (PV plant located in Catania with tracker and useful life of 30 years); CT 30 fixed tilt (PV plant located in Catania with fixed mounting system and useful life of 30 years).

Impact category	PC 30 tracker	PC 30 fixed tilt	CT 30 tracker	CT 30 fixed tilt
Climate change (kg CO2 eq.)	1.92E-02	2.16E-02	1.44E-02	1.74E-02
Ozone depletion (kg CF11 eq.)	1.68E-09	1.90E-09	1.26E-09	1.53E-09
Photochemical ozone formation (kg NMVOC eq.)	7.38E-05	8.24E-05	5.54E-05	6.63E-05
Respiratory inorganics (disease inc.)	1.26E-09	1.41E-09	9.47E-10	1.14E-09
Acidification (mol H+ eq.)	1.18E-04	1.29E-04	8.83E-05	1.04E-04
Freshwater eutrophication (kg P eq.)	7.65E-06	8.32E-06	5.74E-06	6.69E-06
Marine eutrophication (kg N eq.)	3.07E-05	3.40E-05	2.31E-05	2.73E-05
Terrestrial eutrophication (mol N eq.)	2.52E-04	2.83E-04	1.89E-04	2.27E-04
Land use (Pt)	4.30E-01	4.91E-01	3.23E-01	3.95E-01
Resource use, energy carriers (MJ)	2.33E-01	2.63E-01	1.75E-01	2.11E-01
Resource use, mineral and metals (kg Sb eq.)	9.03E-07	9.77E-07	6.78E-07	7.86E-07

Figure 8: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh). Lifetime sensitivity analysis: (a) PV plant located in Piacenza with tracker; (b) PV plant located in Piacenza with modules at fixed tilt; (c) PV located in Catania with tracker; (d) PV plant located in Catania with modules at fixed tilt. Impacts for the 30-year scenario are expressed as a percentage of impacts for the 25-year lifetime scenario.

4.3. Contribution analysis

A contribution analysis was performed to better understand the main criticalities of the system. Figure 9 shows the results regarding the *Climate change* and *Resource use, mineral and metals* impact categories, referred to the FU. In the first category, in all the configurations, the impact associated with the module production (i.e., from the raw material extraction to the module production) covers more than 75% of the total impact. The tracker component covers approximately 10% of the impact due to metal extraction and processing.

In addition, the contribution of the inverter production is significant in the *Resource use, mineral and metals* category. The component is responsible for approximately 30% of the impact, and, in fact, the precious metals involved in the inverter production contribute to a decrease in the environmental performances. Minor impacts are generated by the transport, and end-of-life process, which together generate less than 5% of the total impact.

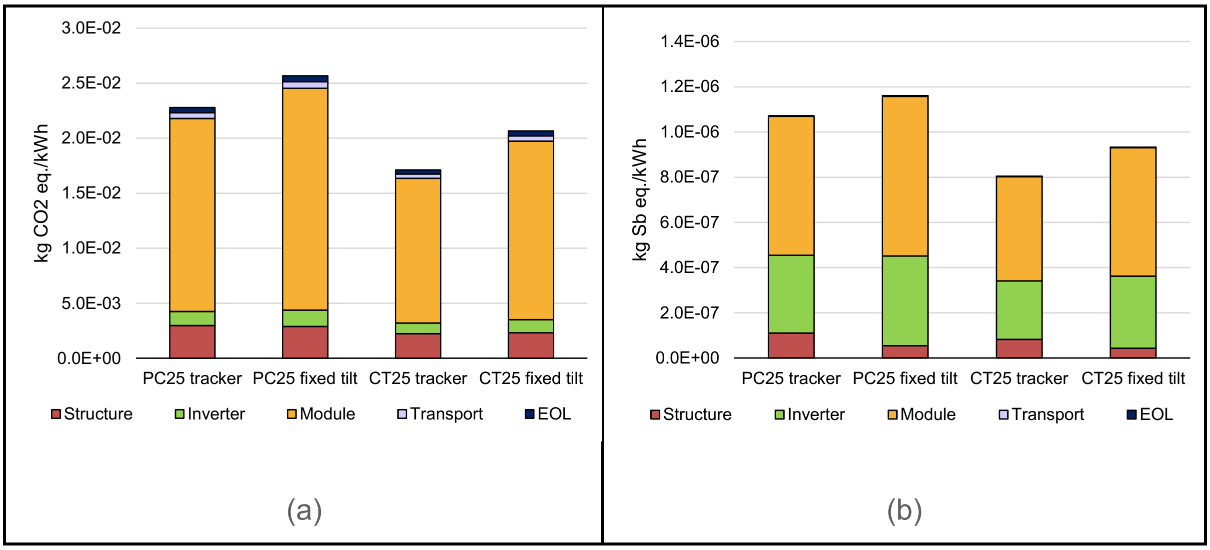


Figure 9: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh). Contribution analysis of the systems: (a) *Climate change* category; (b) *Resource use, mineral and metals*. The results are according to the FU.

A detailed examination of the contribution analysis of the environmental impacts in the *Climate change* category (Figure 10) regarding the production of a single module reveals that the main contribution is associated with cell production (from the raw material extraction to the cell production), which is responsible for 73% of the impacts. The other components and processes (e.g., frame, glass, junction box, end of life) cause less than 30% of the total impacts. The transportation of the module subcomponents (included in the "Other" category in Figure 10) account for approximately 1% of the impacts. For cell manufacturing, significant impacts are caused both by wafer production (approximately 58% of the total greenhouse gases emitted to realise the cell and consequently approximately 42% to make the module) and by the chemicals (i.e., N_2O, NH_3, $POCl_3$.) involved in the cell production process.

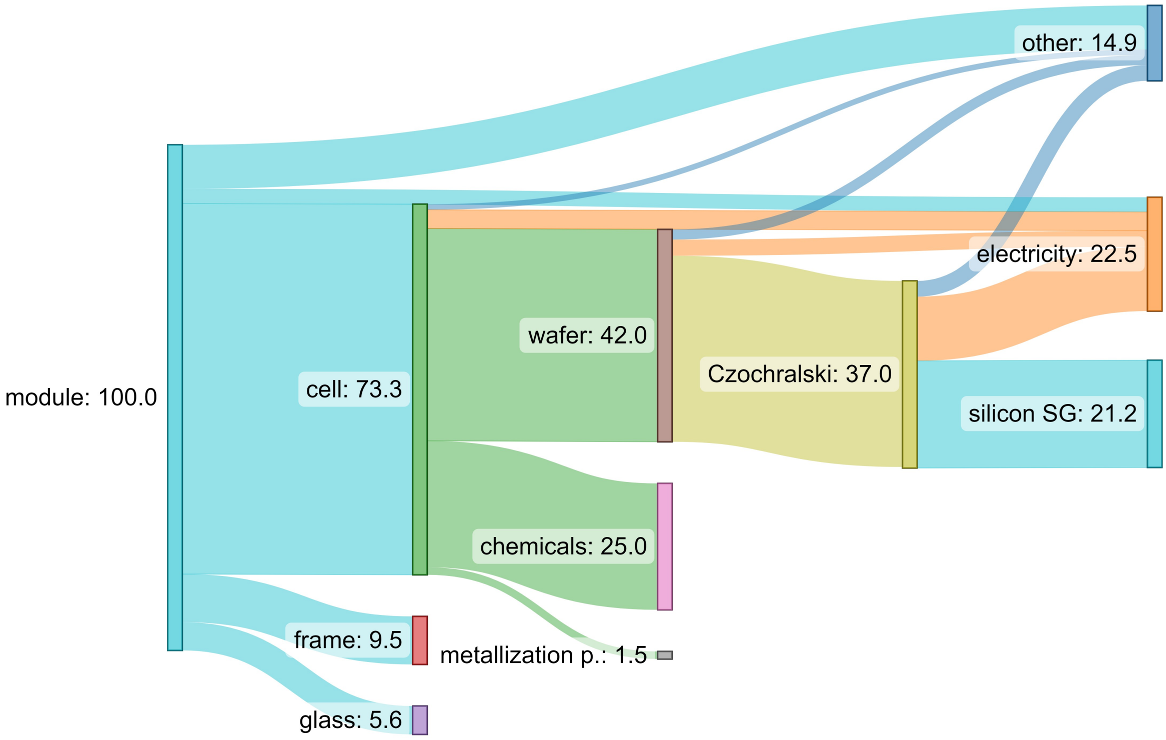


Figure 10: Analysis of contribution to Climate Change for production of PERC modules. Results are expressed as percent.

4.4. Comparison with Al-BSF technology

The potential environmental impacts of the PERC technology are compared with Al-BSF solution. Despite Al-BSF technology is phasing-out, it remains the most investigated technology in the existing LCA studies related to energy scenarios and still often the only one in the most widely used LCA databases (also because in 2019 Al-BSF still accounted for 60% of the market share [31]).The environmental impacts associated with PV plants characterised by conventional Al-BSF modules are shown in Table 12 (modelled according to IEA PVPS LCI [24]).

Table 12: Environmental impacts associated with conventional Al-BSF technology modelled according to IEA LCI [24]**. Four configurations have been investigated: PC IEA 25 tracker (PV plant based on Al-BSF concept located in Piacenza with tracker and useful life of 25 years); PC IEA 25 fixed tilt (PV plant based on Al-BSF concept located in Piacenza with fixed mounting system and useful life of 25 years); CT IEA 25 tracker (PV plant based on Al-BSF concept located in Catania with tracker and useful life of 25 years); CT IEA 25 fixed tilt (PV plant based on Al-BSF concept located in Catania with fixed mounting system and useful life of 25 years).**

Impact category	PC IEA 25 tracker	PC IEA 25 fixed tilt	CT IEA 25 tracker	CT IEA 25 fixed tilt
Climate change (kg CO2 eq.)	2.74E-02	3.05E-02	2.05E-02	2.46E-02
Ozone depletion (kg CF11 eq.)	2.27E-09	2.54E-09	1.70E-09	2.05E-09
Photochemical ozone formation (kg NMVOC eq.)	1.14E-04	1.26E-04	8.53E-05	1.01E-04
Respiratory inorganics (disease inc.)	2.08E-09	2.31E-09	1.56E-09	1.86E-09
Acidification (mol H+ eq.)	1.82E-04	1.97E-04	1.36E-04	1.59E-04
Freshwater eutrophication (kg P eq.)	1.14E-05	1.22E-05	8.54E-06	9.82E-06
Marine eutrophication (kg N eq.)	4.80E-05	5.26E-05	3.60E-05	4.24E-05
Terrestrial eutrophication (mol N eq.)	3.83E-04	4.26E-04	2.87E-04	3.43E-04
Land use (Pt)	4.96E-01	5.62E-01	3.72E-01	4.53E-01
Resource use, energy carriers (MJ)	3.09E-01	3.44E-01	2.32E-01	2.77E-01
Resource use, mineral and metals (kg Sb eq.)	1.38E-06	1.40E-06	1.04E-06	1.13E-06

For each plant configuration, the percentage variation of the impacts was evaluated according to equation (1):

$$\Delta_{impact} = {}^{\mathrm{I}_{PERC}}/_{\mathrm{I}_{BSF}} \qquad (1)$$

I_{PERC} = impact generated by the PERC PV plant

I_{AI-BSF} = impact generated by the Al-BSF PV plant.

The percentage differences of the environmental impacts are presented in Table 13. The use of PERC modules instead of Al-BSF technology appears more beneficial from the environmental point of view. The higher efficiency leads to improvements in environmental performance by more than 15% in 7 of 11 categories.

Table 13: Percentage of the impacts when using PERC modules instead of the conventional Al-BSF for the different plant configurations and impact categories.

Impact category	PC 25 tracker	PC 25 fixed tilt	CT 25 tracker	CT 25 fixed tilt
Climate change (kg CO2 eq.)	86%	86%	86%	86%
Ozone depletion (kg CF11 eq.)	88%	89%	88%	88%
Photochemical ozone formation (kg NMVOC eq.)	77%	78%	77%	78%
Respiratory inorganics (disease inc.)	72%	73%	72%	73%
Acidification (mol H+ eq.)	77%	78%	77%	78%
Freshwater eutrophication (kg P eq.)	80%	81%	80%	81%
Marine eutrophication (kg N eq.)	76%	77%	76%	77%
Terrestrial eutrophication (mol N eq.)	78%	79%	78%	79%
Land use (Pt)	87%	88%	87%	88%
Resource use, energy carriers (MJ)	90%	91%	90%	91%
Resource use, mineral and metals (kg Sb eq.)	78%	83%	77%	83%

5. CONCLUSIONS

This study presented an LCA of a ground-mounted (half-cells) PERC module-based PV plant in two locations in Italy. A key element of the study is that primary data is used. As far as the *Climate Change* impact category, results ranging between 25.7 g CO_2 eq. /kWh (PV plant located in Piacenza and with modules at fixed tilt) and 17.1 g CO_2 eq. /kWh (PV plant located in Catania and equipped with mono-axial solar tackers) have been obtained. In general, the potential environmental impacts generated by the PERC utility-scale plant are lower than the values reported in literature studies on c-Si LCA, which consider a module efficiency between 12% and 17% and a GHI ranging between 1697 and 1800 kWh/m^2/y (Figure 11). The differences in terms of global warming potentials are associated with different module efficiency and GHI which directly affect the electricity produced over the lifetime of the PV plant [7]. Focusing on the contribution analysis, the studies indicate that the energy consumption, coming from the production and manufacturing phases, is a critical hotspot of the entire life cycle, as obtained in the present study. Consequently, although the manufacturing processes has been already improved, additional measures (e.g., the use of low-carbon energy mix in the production of silicon ingot) could further reduce emissions.

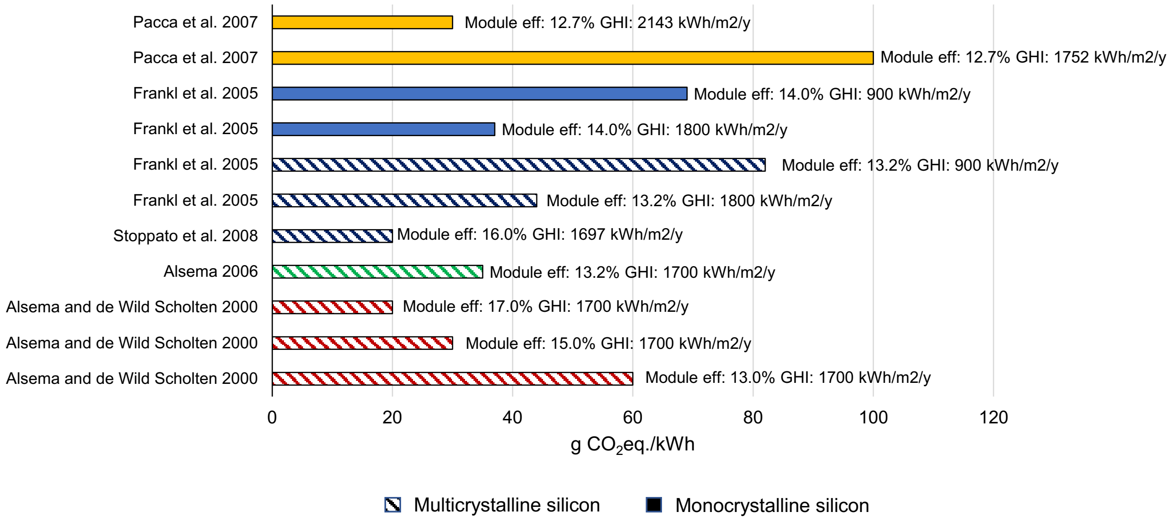


Figure 11: Comparison with literature focused on c-Si LCA and referred to the Al-BSF technology [7]

The comparison with other PERC LCA study (Table 14) shows that the results are in accordance with most recent LCA studies on PERC technology, Lunardi et al. [32] estimate 19-26 g CO_2 eq. /kWh assuming 1,700 kWh/m^2/year annual insolation, 0.75 performance ratio and 25 years lifetime while Jia et al. [33] assess greenhouse gas emissions between 18 and 27 g CO_2 eq. /kWh for PV systems installed in Beijing (solar irradiance 1573 kWh/m^2/year) and with a lifetime of 25-30 years.

Table 14: Comparison with other studies on LCA of PERC module.

Reference	Module type	Nominal power of the module (W)	Lifetime (y)	GHI (kWh/m^2/y)	FU	GWP (g CO2eq.)
Jia et al. 2021 [33]	PERC mono-facial, ground mounted	340 ÷ 405	25	1573	1 kWh	26.5 ÷ 27.0
	PERC bi-facial, ground mounted	345 ÷ 500	30	1573	1 kWh	18.4 ÷ 20.0
Lunardi et al. 2018 [32]	PERC (EGS feedstock)	NA	25	1700	1 kWh	26.0
	PERC (SGS feedstock)	NA	25	1700	1 kWh	19.9
	PERC (UMG-Si feedstock)	NA	25	1700	1 kWh	19.8
Luo et al. 2018 [34]	PERC mono-facial, roof-integrated	244	30	1580	1 kWh	29.2
	PERC bi-facial, roof-integrated	238	30	1580	1 kWh	20.9

In conclusion, the study demonstrates that the use of state-of-the-art PERC modules with high efficiency considerably reduces the environmental burdens — and in particular the *Carbon Footprint* — of electricity produced compared with PV systems with “standard” modules. Moreover, the analysis of two different mounting systems (fixed tilt and tracker) shows that the solution with modules mounted on a mono-axial solar tracker is preferable from an environmental point of view, at least at latitudes like those in Italy[10].

Finally, a sensitivity analysis on expected panel lifetime suggests that extending the service lifetime of PV panels helps reduce the specific environmental impacts per kWh. In other words, the longer the panels’ lifetime, the lower the impacts per kWh.

---

[10] If wind conditions allow the profitable use of the tracker, considering that it must be put in a safe position with wind speed over a certain threshold.

6. REFERENCES

[1] G. Masson, E. Bosch, A. Van Rechem, and M. de l'Epine, '2023 Snapshot of Global PV Markets'. Report IEA-PVPS T1-44:2023, p. 21, 2023.

[2] G. Masson, M. de l'Epine, and I. Kaizuka, 'Trends in photovoltaic applications 2023'. Report IEA PVPS T1-43:2023, p. 96, 2023.

[3] N. A. Ludin *et al.*, 'Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review', *Renew. Sustain. Energy Rev.*, vol. 96, pp. 11–28, Nov. 2018, doi: 10.1016/j.rser.2018.07.048.

[4] Ministry of Economic Development, 'Integrated National Energy and Climate Plan', Rome, 2019. Accessed: Feb. 23, 2021. [Online]. Available: https://www.mise.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf.

[5] V. Muteri *et al.*, 'Review on life cycle assessment of solar photovoltaic panels', *Energies*, vol. 13, no. 1, 2020, doi: 10.3390/en13010252.

[6] M. (Hanwha Q. C. G. Fischer, M. (The N. R. E. L. Woodhouse, S. (VDMA P. E. Herritsch, and J. (VDMA P. E. Trube, 'International Technology Roadmap for Photovoltaic. 2020 Results', Frankfurt am Main, 2021.

[7] D. D. Hsu *et al.*, 'Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation: Systematic Review and Harmonization', *J. Ind. Ecol.*, vol. 16, no. SUPPL.1, 2012, doi: 10.1111/j.1530-9290.2011.00439.x.

[8] International Organization for Standardization, 'ISO 14040: Environmental management–life cycle assessment—Principles and framework', *Int. Organ. Stand.*, vol. 2006, 2006.

[9] International Organization for Standardization, 'ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines', *Int. Organ. Stand.*, vol. 2006, no. 7555, p. 1418.1, 2006, doi: 10.1136/bmj.332.7555.1418.

[10] R. Frischknecht, P. Stolz, G. Heath, M. Raugei, P. Sinha, and M. de Wild-Scholten, 'Methodology guidelines on life cycle assessment of photovoltaic electricity', *IEA PVPS Task 12, International Energy Agency Photovoltaic Power Systems Programme*. 2020.

[11] M. Fischer, M. Woodhouse, P. Baliozian, and J. Trube, 'International Technology Roadmap for Photovoltaic (ITRPV) 14th Edition', *ITRPV 2023*. VDMA e.V. Photovoltaic Equipment, p. 81, 2023.

[12] T. Huld, R. Müller, and A. Gambardella, 'A new solar radiation database for estimating PV performance in Europe and Africa', *Sol. Energy*, vol. 86, no. 6, pp. 1803–1815, Jun. 2012, doi: 10.1016/j.solener.2012.03.006.

[13] T. Ekvall, A. Azapagic, G. Finnveden, T. Rydberg, B. P. Weidema, and A. Zamagni, 'Attributional and consequential LCA in the ILCD handbook', *Int. J. Life Cycle Assess.*, vol. 21, no. 3, pp. 293–296, Mar. 2016, doi: 10.1007/s11367-015-1026-0.

[14] IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, vol. In Press. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021.

[15] WMO, 'Scientific Assessment of Ozone Depletion', Geneva, Switzerland, 1998. Accessed: Feb. 18, 2021. [Online]. Available: https://library.wmo.int/?lvl=notice_display&id=15453#.YC4mp3nSKUl.

[16] R. van Zelm *et al.*, 'European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment', *Atmos. Environ.*, vol. 42, no. 3, pp. 441–453, Jan. 2008, doi: 10.1016/j.atmosenv.2007.09.072.

[17] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, 'ReCiPe 2008', *Potentials*, no. May 2014, pp. 1–44, 2009, [Online]. Available: http://www.pre-sustainability.com/download/misc/ReCiPe_main_report_final_27-02-2009_web.pdf.

[18] M. Posch, J. Seppälä, J.-P. Hettelingh, M. Johansson, M. Margni, and O. Jolliet, 'The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA', *Int. J. Life Cycle Assess.*, vol. 13, no. 6, p. 477, 2008, doi: 10.1007/s11367-008-0025-9.

[19] J. Seppälä, M. Posch, M. Johansson, and J.-P. Hettelingh, 'Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 pp)', *Int. J. Life Cycle Assess.*, vol. 11, no. 6, pp. 403–416, 2006, doi: 10.1065/lca2005.06.215.

[20] J. Struijs, A. Beusen, D. De Zwart, and M. Huijbregts, 'Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment', *Int. J. Life Cycle Assess.*, vol. 16, no. 1, pp. 59–64, 2011, doi: 10.1007/s11367-010-0232-z.

[21] J. B. Guinée, 'Handbook on life cycle assessment - Operational guide to the ISO standards', *International Journal of Life Cycle Assessment*, vol. 6, no. 5. Springer Verlag, p. 255, 2001, doi: 10.1007/BF02978784.

[22] L. van Oers, A. de Koning, J. B. Guinée, and G. Huppes, 'Abiotic Resource Depletion in LCA: Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA Handbook', *Road Hydraul. Eng. Inst.*, no. June, pp. 1–75, 2002, [Online]. Available: https://www.leidenuniv.nl/cml/ssp/projects/lca2/report_abiotic_depletion_web.pdf.

[23] C. Breyer and J. Schmid, 'Population Density and Area Weighted Solar Irradiation: Global Overview on Solar Resource Conditions for Fixed Tilted, 1-Axis and 2-Axes PV Systems.', in *25th European Photovoltaic Solar Energy Conference and Exhibition*, 2010, no. September, pp. 4692–4709, doi: 10.4229/25thEUPVSEC2010-4BV.1.91.

[24] R. Frischknecht *et al.*, 'Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems 2020'. International Energy Agency (IEA) PVPS Task 12, Report T12-19:2020, p. 89, 2020.

[25] M. Woodhouse, B. Smith, A. Ramdas, and Robert Margolis, 'Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Roadmap', *Natl. Renew. Energy Lab.*, no. February, pp. 1–46, 2019, [Online]. Available: https://www.nrel.gov/docs/fy19osti/72134.pdf.%0ANREL.

[26] C. C. Farrell *et al.*, 'Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules', *Renew. Sustain. Energy Rev.*, vol. 128, p. 109911, 2020, doi: 10.1016/j.rser.2020.109911.

[27] R. Frischknecht *et al.*, 'Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems'. International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015, p. 86, 2015.

[28] A. Müller, L. Friedrich, C. Reichel, S. Herceg, M. Mittag, and D. H. Neuhaus, 'Solar Energy Materials and Solar Cells A comparative life cycle assessment of silicon PV modules : Impact of module design , manufacturing location and inventory', *Sol. Energy Mater. Sol. Cells*, vol. 230, no. June, p. 111277, 2021, doi: 10.1016/j.solmat.2021.111277.

[29] B. L. Smith *et al.*, 'Photovoltaic (PV) Module Technologies : 2020 Benchmark Costs and Technology Evolution Framework Results Photovoltaic (PV) Module Technologies : 2020 Benchmark Costs and Technology Evolution Framework Results', no. November, 2021.

[30] S. Manfredi, K. Allacker, K. Chomkhamsri, N. Pelletier, and D. Maia De Souza, 'Product Environmental Footprint (PEF) Guide Institute for Environment and Sustainability (IES) Product Environmental Footprint Guide; CONSOLIDATED VERSION', 2012.

[31] X. Jia, F. Lv, P. Li, and W. Wang, 'Life-cycle assessment of p-type multi-Si back surface field

(BSF) solar module in China of 2019', *Sol. Energy*, vol. 196, 2020, doi: 10.1016/j.solener.2019.12.018.

[32] M. M. Lunardi, J. P. Alvarez-Gaitan, N. L. Chang, and R. Corkish, 'Life cycle assessment on PERC solar modules', *Sol. Energy Mater. Sol. Cells*, vol. 187, no. August, pp. 154–159, 2018, doi: 10.1016/j.solmat.2018.08.004.

[33] X. Jia, C. Zhou, Y. Tang, and W. Wang, 'Life cycle assessment on PERC solar modules', *Sol. Energy Mater. Sol. Cells*, vol. 227, no. October 2020, p. 111112, 2021, doi: 10.1016/j.solmat.2021.111112.

[34] W. Luo *et al.*, 'A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies', *Sol. Energy Mater. Sol. Cells*, vol. 174, no. January 2017, pp. 157–162, 2018, doi: 10.1016/j.solmat.2017.08.040.

[35] 'PV Panels SILK® Pro 440-460 Wp Monocrystalline | FuturaSun'. https://www.futurasun.com/en/products/monocrystalline-pv-panels/silk-pro-144-multi-busbar-half-cut-cells/ (accessed Aug. 30, 2023).

[36] JRC European commission, *ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context*. 2011.

ANNEX 1 – LIFE CYCLE IMPACT ASSESSMENT

The environmental performances obtained for the 16 indicators selected according to the IEA Methodology Guidelines are shown in

Table **15**. The impacts are referred to electricity production generated by the following plants:

- PC 25 tracker: PV plant located in Piacenza with tracker and useful life of 25 years;
- PC 25 fixed tilt: PV plant located in Piacenza with fixed mounting system and useful life of 25 years;
- PC 30 tracker: PV plant located in Piacenza with tracker and useful life of 30 years;
- PC 30 fixed tilt: PV plant located in Piacenza with fixed mounting system and useful life of 30 years;
- CT 25 tracker: PV plant located in Catania with tracker and useful life of 25 years;
- CT 25 fixed tilt: PV plant located in Catania with fixed mounting system and useful life of 25 years;
- CT 30 tracker: PV plant located in Catania with tracker and useful life of 30 years;
- CT 30 fixed tilt: PV plant located in Catania with fixed mounting system and useful life of 30 years.

Table 15: Environmental impact of ground mounted PV electricity with PERC modules (FU 1kWh). Comparison of the potential environmental impacts associated with the eight PV plant configurations.

Impact categories	PC				CT			
	25 tracker	25 fixed tilt	30 tracker	30 fixed tilt	25 tracker	25 fixed tilt	30 tracker	30 fixed tilt
Climate change (kg CO2 eq.)	2.28E-02	2.57E-02	1.92E-02	2.16E-02	1.71E-02	2.07E-02	1.44E-02	1.74E-02
Ozone depletion (kg CFC11 eq)	1.99E-09	2.25E-09	1.68E-09	1.90E-09	1.50E-09	1.81E-09	1.26E-09	1.53E-09
Ionising radiation (kBq U-235 eq)	1.43E-03	1.57E-03	1.20E-03	1.33E-03	1.07E-03	1.27E-03	9.02E-04	1.07E-03
Photochemical ozone formation (kg NMVOC eq)	8.75E-05	9.78E-05	7.38E-05	8.24E-05	6.57E-05	7.86E-05	5.54E-05	6.63E-05
Particulate matter (disease inc.)	1.50E-09	1.68E-09	1.26E-09	1.41E-09	1.12E-09	1.35E-09	9.47E-10	1.14E-09
Human toxicity, non-cancer (CTUh)	5.72E-10	5.94E-10	4.82E-10	5.00E-10	4.29E-10	4.77E-10	3.62E-10	4.02E-10
Human toxicity, cancer (CTUh)	4.27E-11	4.49E-11	3.60E-11	3.78E-11	3.21E-11	3.61E-11	2.70E-11	3.04E-11
Acidification (mol H+ eq.)	1.40E-04	1.54E-04	1.18E-04	1.29E-04	1.05E-04	1.24E-04	8.83E-05	1.04E-04
Freshwater eutrophication (kg P eq)	9.07E-06	9.88E-06	7.65E-06	8.32E-06	6.81E-06	7.94E-06	5.74E-06	6.69E-06
Marine eutrophication (kg N eq.)	3.64E-05	4.04E-05	3.07E-05	3.40E-05	2.73E-05	3.25E-05	2.31E-05	2.73E-05
Terrestrial eutrophication (mol N eq.)	2.99E-04	3.36E-04	2.52E-04	2.83E-04	2.25E-04	2.70E-04	1.89E-04	2.27E-04
Freshwater ecotoxicity (CTUe)	8.96E-01	9.80E-01	7.56E-01	8.26E-01	6.73E-01	7.88E-01	5.67E-01	6.64E-01
Land use (Pt)	4.33E-01	4.94E-01	4.30E-01	4.91E-01	3.25E-01	3.98E-01	3.23E-01	3.95E-01
Water use (m3 depriv.)	1.08E-02	1.22E-02	9.10E-03	1.03E-02	8.11E-03	9.78E-03	6.83E-03	8.24E-03
Resource use, fossils (MJ)	2.77E-01	3.12E-01	2.33E-01	2.63E-01	2.08E-01	2.51E-01	1.75E-01	2.11E-01
Resource use, minerals and metals (kg Sb eq.)	1.07E-06	1.16E-06	9.03E-07	9.77E-07	8.04E-07	9.33E-07	6.78E-07	7.86E-07

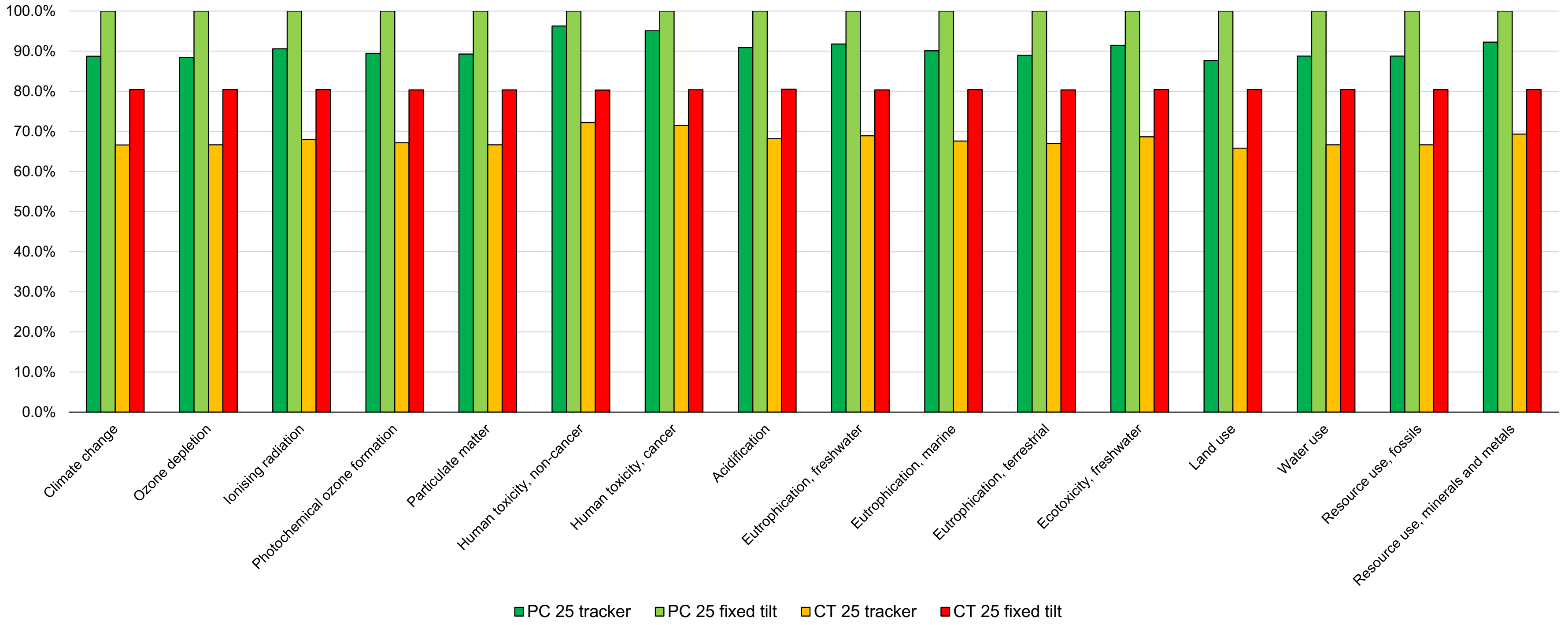


Figure 12: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh) and lifetime of 25 years. Comparison of the potential environmental impacts associated with the four PV plant configurations. The worst solution is set equal to 100%.

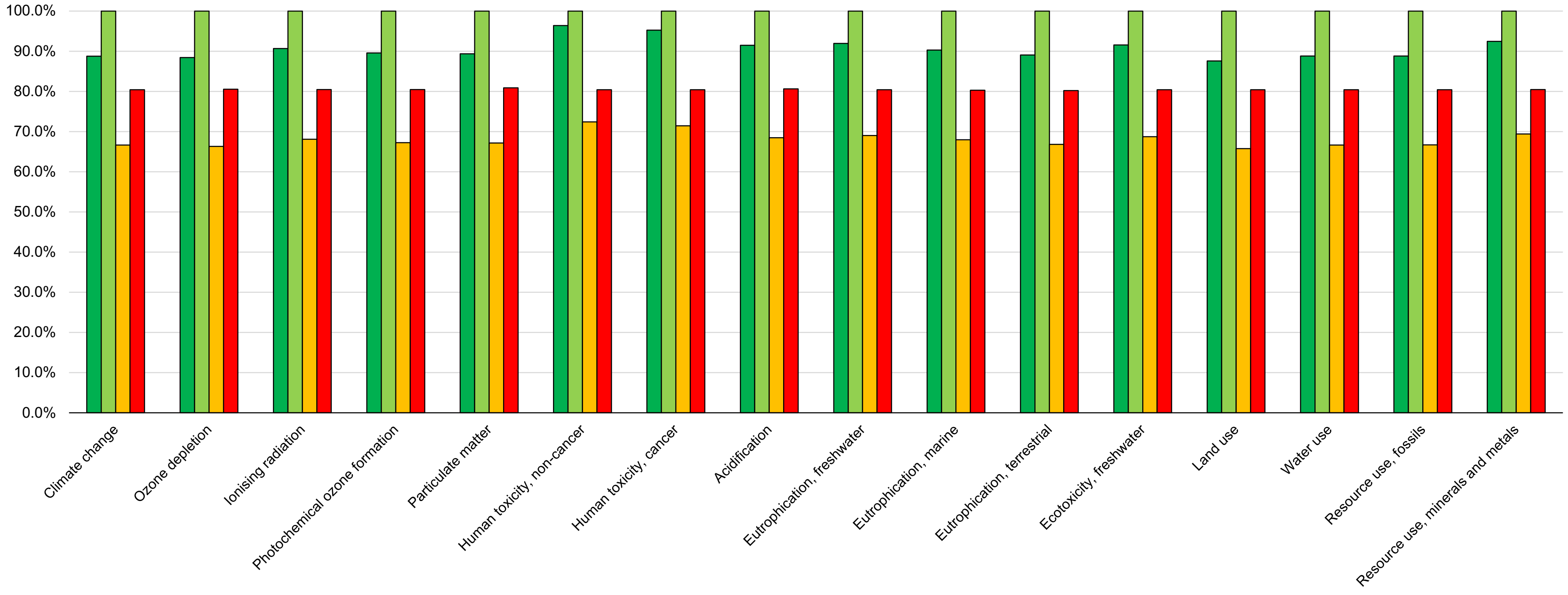
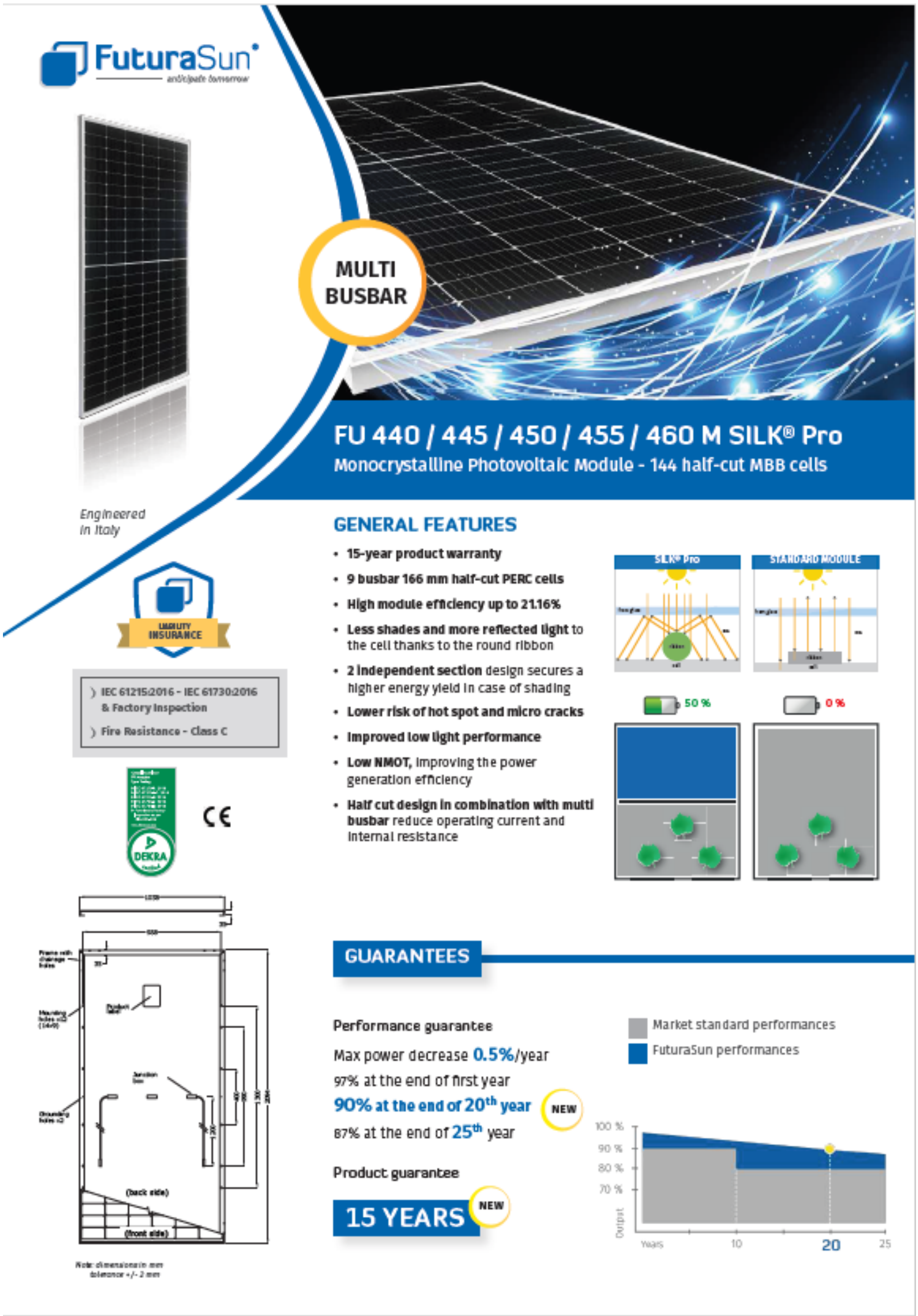


Figure 13: LCIA of ground mounted PV electricity with PERC modules (FU 1kWh) and lifetime of 30 years. Comparison of the potential environmental impacts associated with the four PV plant configurations. The worst solution is set equal to 10

ANNEX 2 – FUTURASUN SILKPRO MODULE DATA SHEET

The technical data sheet related to the FU 460 M Silk Pro module is shown below [35].



FU 440 / 445 / 450 / 455 / 460 M SILK® Pro

Monocrystalline Photovoltaic Module - 144 half-cut MBB cells

Engineered in Italy

IEC 61215:2016 - IEC 61730:2016 & Factory Inspection

Fire Resistance - Class C

Note: dimensions in mm tolerance +/- 2 mm

GENERAL FEATURES

- **15-year product warranty**
- **9 busbar 166 mm half-cut PERC cells**
- **High module efficiency up to 21.16%**
- **Less shades and more reflected light** to the cell thanks to the round ribbon
- **2 independent section** design secures a higher energy yield in case of shading
- **Lower risk of hot spot and micro cracks**
- **Improved low light performance**
- **Low NMOT,** improving the power generation efficiency
- **Half cut design in combination with multi busbar** reduce operating current and internal resistance

GUARANTEES

Performance guarantee

Max power decrease 0.5%/year

97% at the end of first year

90% at the end of 20th year NEW

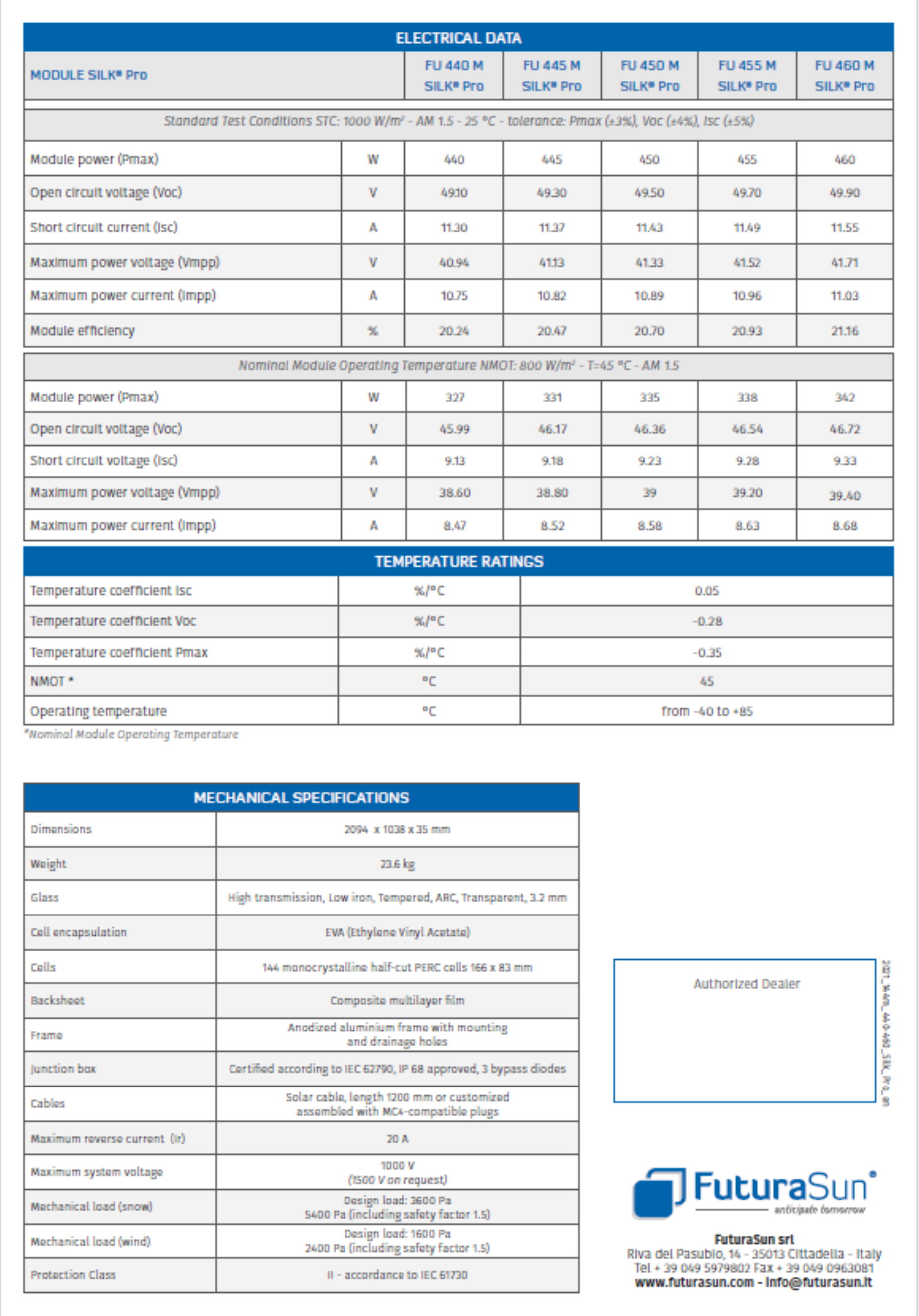
87% at the end of 25th year

Product guarantee

15 YEARS NEW

▨ Market standard performances

■ FuturaSun performances



ELECTRICAL DATA						
MODULE SILK® Pro		FU 440 M SILK® Pro	FU 445 M SILK® Pro	FU 450 M SILK® Pro	FU 455 M SILK® Pro	FU 460 M SILK® Pro
Standard Test Conditions STC: 1000 W/m² - AM 1.5 - 25 °C - tolerance: Pmax (±3%), Voc (±4%), Isc (±5%)						
Module power (Pmax)	W	440	445	450	455	460
Open circuit voltage (Voc)	V	49.10	49.30	49.50	49.70	49.90
Short circuit current (Isc)	A	11.30	11.37	11.43	11.49	11.55
Maximum power voltage (Vmpp)	V	40.94	41.13	41.33	41.52	41.71
Maximum power current (Impp)	A	10.75	10.82	10.89	10.96	11.03
Module efficiency	%	20.24	20.47	20.70	20.93	21.16
Nominal Module Operating Temperature NMOT: 800 W/m² - T=45 °C - AM 1.5						
Module power (Pmax)	W	327	331	335	338	342
Open circuit voltage (Voc)	V	45.99	46.17	46.36	46.54	46.72
Short circuit voltage (Isc)	A	9.13	9.18	9.23	9.28	9.33
Maximum power voltage (Vmpp)	V	38.60	38.80	39	39.20	39.40
Maximum power current (Impp)	A	8.47	8.52	8.58	8.63	8.68

TEMPERATURE RATINGS		
Temperature coefficient Isc	%/°C	0.05
Temperature coefficient Voc	%/°C	-0.28
Temperature coefficient Pmax	%/°C	-0.35
NMOT *	°C	45
Operating temperature	°C	from -40 to +85

*Nominal Module Operating Temperature

MECHANICAL SPECIFICATIONS	
Dimensions	2094 x 1038 x 35 mm
Weight	23.6 kg
Glass	High transmission, Low iron, Tempered, ARC, Transparent, 3.2 mm
Cell encapsulation	EVA (Ethylene Vinyl Acetate)
Cells	144 monocrystalline half-cut PERC cells 166 x 83 mm
Backsheet	Composite multilayer film
Frame	Anodized aluminium frame with mounting and drainage holes
Junction box	Certified according to IEC 62790, IP 68 approved, 3 bypass diodes
Cables	Solar cable, length 1200 mm or customized assembled with MC4-compatible plugs
Maximum reverse current (Ir)	20 A
Maximum system voltage	1000 V *(1500 V on request)*
Mechanical load (snow)	Design load: 3600 Pa 5400 Pa (including safety factor 1.5)
Mechanical load (wind)	Design load: 1600 Pa 2400 Pa (including safety factor 1.5)
Protection Class	II - accordance to IEC 61730

Authorized Dealer

2021_144m_440-460_Silk_Pro_en

FutureSun
anticipate tomorrow

FuturaSun srl
Riva del Pasubio, 14 - 35013 Cittadella - Italy
Tel + 39 049 5979802 Fax + 39 049 0963081
www.futurasun.com - info@futurasun.it

Technology Collaboration Programme
by iea

ISBN 978-3-907281-47-5