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Assessing the environmental impact of photovoltaic technologies: a Life Cycle Assessment-based evaluation framework and its application to multiregional scenarios

MASTER OF SCIENCE'S THESIS IN
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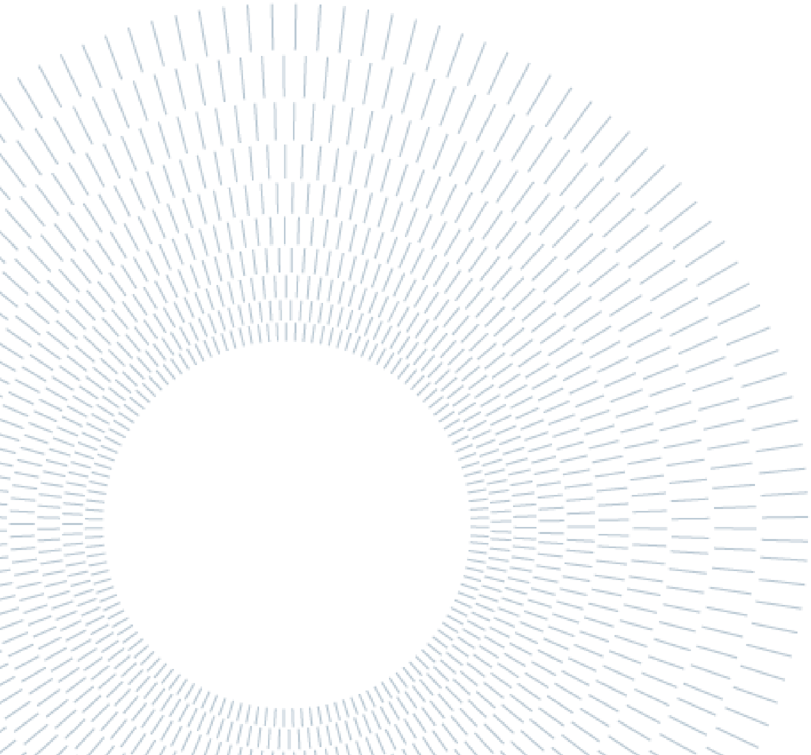


Abstract

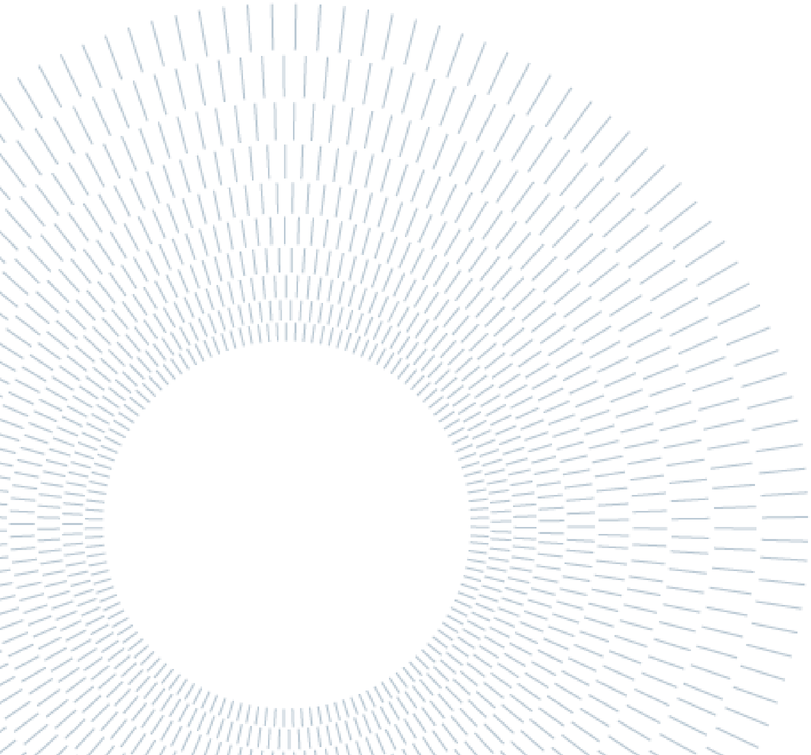
Solar photovoltaic (PV) is seen as a valuable technology to decarbonize the energy sector. In this context, and considering the continuously evolving technology, it is crucial to complete updated assessments of its environmental sustainability. Life Cycle Assessment (LCA) is regarded as the most adopted methodology to evaluate the environmental impact of a product over its life cycle. Starting from an extensive literature review, it emerges a scarcity of studies covering the full life cycle or comparing different PV technologies, as well as the shortage and the limitations of existing LCA-based models, that enable a broad-scope assessment of such technologies. To tackle the gaps, a novel evaluation framework is developed, enabling to compare the life cycle impact of the six main PV technologies through different energy (cumulative energy demand, energy payback time) and greenhouse gas (global warming potential, CO_2 payback time) related indicators. The framework is then applied to a utility-scale plant installed in Italy, with reference to five supply chain scenarios. Results demonstrate the inexistence of a PV technology outperforming the others across all impact indicators. In addition, the analysis highlights the significant influence of the manufacturing phase on the environmental impact and the relevance of the grid carbon intensity of the manufacturing country on greenhouse gas related indicators. Lastly, it is confirmed that PV is a valuable technology to fight climate change, and it is demonstrated how material recycling can further reduce the environmental impact of PV technologies. The study provides suggestions for players in the PV industry and policymakers. For the former, it suggests options to reduce the environmental impact of components. For the latter, the thesis reaffirms the potential of PV in fighting climate change, demonstrates the benefits arising from the development of a PV supply chain in countries characterized by a cleaner electricity mix compared to China, and highlights the importance of further promoting the decarbonization of the electricity sector.

Key-words: life cycle assessment; photovoltaic; environmental impact; global warming potential; energy payback time.

Abstract in italian

Il solare fotovoltaico (PV) è ritenuto una valida tecnologia per decarbonizzare il settore energetico. In tale contesto, e considerando la continua evoluzione tecnologica, è cruciale svolgere valutazioni aggiornate della sua sostenibilità ambientale. L'Analisi del Ciclo di Vita (LCA) è la metodologia più diffusa per valutare l'impatto ambientale di un prodotto. Dall'analisi della letteratura, si osserva una carenza di studi che coprono l'intero ciclo di vita o che comparano più tecnologie PV, oltre che la scarsità e le limitazioni dei modelli LCA esistenti, che permettono un'analisi ad ampio spettro di tali tecnologie. Per contrastare le limitazioni osservate, viene sviluppato un modello che permette di comparare l'impatto lungo il ciclo di vita delle sei principali tecnologie PV rispetto a indicatori energetici (richiesta cumulativa di energia, tempo di ritorno energetico) e relativi alle emissioni (potenziale di riscaldamento globale, tempo di ritorno in CO_2). Il modello è applicato ad un impianto di larga scala in Italia, relativamente a cinque scenari di filiera. I risultati dimostrano l'assenza di una tecnologia più performante delle altre rispetto a tutti gli indicatori. Inoltre, si evidenzia l'influenza significativa della fase di produzione sull'impatto ambientale e la rilevanza dell'intensità carbonica della rete elettrica del paese di produzione sugli indicatori relativi alle emissioni. Infine, si conferma che il PV è una valida tecnologia nella lotta al cambiamento climatico e si dimostra come il riciclo dei materiali possa ridurre ulteriormente l'impatto ambientale del fotovoltaico. La tesi offre suggerimenti ad attori nell'industria PV e ai decisori politici. Per i primi, si propongono opzioni per ridurre l'impatto ambientale dei componenti. Per i secondi, la tesi conferma il potenziale del PV nella lotta al cambiamento climatico, dimostra i benefici legati allo sviluppo di un'industria PV in paesi con un mix elettrico più pulito rispetto alla Cina, ed evidenzia l'importanza di sostenere la decarbonizzazione del sistema elettrico.

Parole chiave: analisi del ciclo di vita; fotovoltaico; impatto ambientale; potenziale di riscaldamento globale; tempo di ritorno energetico.



Contents

Abstract .... **i**

Abstract in italian .... **iii**

Contents .... **v**

1 Introduction **1**

- 1.1. The context 1
- 1.2. Overview of photovoltaic technologies 2
  - 1.2.1. Global PV installed capacity and market segments 4
  - 1.2.2. Components of a PV system 6
- 1.3. The environmental sustainability of PV technologies 7
  - 1.3.1. The environmental impact of PV technologies 8
  - 1.3.2. The importance of the LCA for PV technologies 11
- 1.4. The LCA methodology 12
  - 1.4.1. The steps composing an LCA analysis 12

2 Literature review **17**

- 2.1. Process followed 17
- 2.2. Full text analysis 20
  - 2.2.1. Introductory information 21
  - 2.2.2. Methodological aspects 22
  - 2.2.3. PV system hypothesis 33
  - 2.2.4. PV technical parameters 41
  - 2.2.5. Modeling approaches 44
- 2.3. Gaps identified in the literature 64
- 2.4. Research questions 65

3 Methodology **67**

- 3.1. Introduction 67

3.2. Evaluation framework development ... 67
3.3. Evaluation framework application ... 67
4 Evaluation framework development ... 69
4.1. Evaluation framework overview ... 69
4.2. Electricity production ... 70
4.3. Modules manufacturing ... 72
4.4. BOS manufacturing ... 79
4.5. Transportation ... 82
4.6. Installation ... 88
4.7. Use ... 90
4.8. End-of-life ... 94
4.9. Evaluation framework recap ... 103
  4.9.1. Input variables ... 103
  4.9.2. Impact indicators ... 106
5 Evaluation framework application ... 111
5.1. Introduction ... 111
5.2. Definition of scenarios ... 111
  5.2.1. Mixed supply scenario ... 115
  5.2.2. Chinese supply scenario ... 116
  5.2.3. Out-of-Asia supply scenario ... 117
  5.2.4. German supply scenario ... 117
  5.2.5. Italian supply scenario ... 118
5.3. Results and discussion ... 120
  5.3.1. Monocrystalline ... 120
  5.3.2. Multicrystalline ... 125
  5.3.3. a-Si ... 129
  5.3.4. CIS ... 134
  5.3.5. CdTe ... 138
  5.3.6. OPV ... 142

5.3.7. Comparisons of results 146
5.4. Sensitivity analysis 153
5.4.1. Irradiation 155
5.4.2. Modules conversion efficiency 158
5.4.3. Benefits from the end-of-life phase 162
6 Conclusions 171
6.1. Bottom line results 171
6.2. Industrial and policymaking implications 177
6.3. Limitations and avenues for future research 178
Bibliography 181
Appendix 207
Appendix A.1: Literature review table 207
Appendix A.2: Impact of the life cycle phases 221
Appendix A.3: CED for Modules manufacturing 226
List of Figures 227
List of Tables 233
List of Acronyms 235
Acknowledgments 239

1 Introduction

1.1. The context

Most of the energy fueling our society comes from polluting fossil fuels: according to the International Energy Agency (IEA), 78% of the worldwide total energy supply was satisfied by oil, coal, and gas in 2021 (1). This has consequences on the environment: burning fossil fuels for energy generation leads to the release of greenhouse gases (GHG) in the atmosphere. In particular, the most updated report from the International Panel on Climate Change shows that in 2019 the atmospheric CO_2 concentration was higher than at any time in the last 2 million years and that it is 'unequivocal that human influence has warmed the atmosphere, ocean and land' (2). Climate change is already affecting every inhabited region worldwide and represents a threat to life on the planet with effects such as hot extremes, heavy precipitations, agricultural and ecological droughts (2).

At the COP[1] 21 in December 2015, 195 nations adopted the Paris Agreement to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels (3). CO_2 produced from human activity is the strongest contributor to climate change and emissions from energy use are the largest contributor to those emissions (4): most recent data from the World Resource Institute indicate that emissions from energy use accounted for 75% of all CO_2 equivalent emissions in 2019 (5).

Thus, it is possible to understand the importance of the decarbonization of the energy sector. The Net Zero by 2050 Scenario from the IEA shows an ambitious roadmap for the global energy sector to be consistent with efforts to limit the global warming below 1.5 °C (1). The scenario is very ambitious in terms of solar photovoltaic (PV), becoming the largest contributor to the global electricity generation (37% of the total) in 2050, while accounting for only 4% in 2021 (1). Also considering a more conservative scenario, such as the Stated Policies Scenario from the World Energy Outlook 2022, which explores how the energy system might evolve without additional policy implementation, solar PV is expected to account for the largest share of installed capacity (24%) and electricity generation (38%) across all power generation technologies by 2050 (1). Considering the Italian

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[1] COP: Conference of the Parties

context, solar PV represents the renewable energy with the highest installed capacity as of end 2021 (6). Furthermore, it is expected to grow more than twofold by 2030, reaching 50 GW of capacity according to targets of the National Energy and Climate Plan (NECP), thus becoming the renewable source accounting for the largest share of installed capacity and electricity production (7) (8).

After this brief introduction demonstrating the relevant role expected by photovoltaic in the decarbonization of the energy sector, the following section will provide an overview of photovoltaic technologies.

1.2. Overview of photovoltaic technologies

It is possible to harness energy from the sun in several ways, including (9):

- Solar heating: to heat up water (9).
- Photovoltaic (PV): to generate electricity thanks to the photovoltaic effect (9).
- Concentrated solar power (CSP): to generate electricity thanks to a fluid heated by solar rays (9).

The present thesis will focus on photovoltaic electricity generation: as a matter of fact, the total installed solar PV capacity exceeds 800 GW, while less than 7 GW of CSP are installed worldwide as of end 2021 (6). The relevant role played by photovoltaic within the solar energy landscape is confirmed also by the Italian context: as of the end of 2021, 22.7 GW of photovoltaic and only 6 MW of CSP are installed in Italy (10) (6). Solar PV technologies are usually classified into three generations (11) (12) (13):

1. First generation solar cells.

   First generation solar cells are also called crystalline silicon (c-Si) cells and account for over 95% of the overall cell production in 2021 (14) (11). c-Si technologies include monocrystalline and multicrystalline cells (15) (14). The former features efficiencies between 20% and 25% and account for over 85% of the c-Si share (14). Multicrystalline silicon cells features lower production costs but are less efficient, featuring efficiencies ranging from 18% to 21% (14).

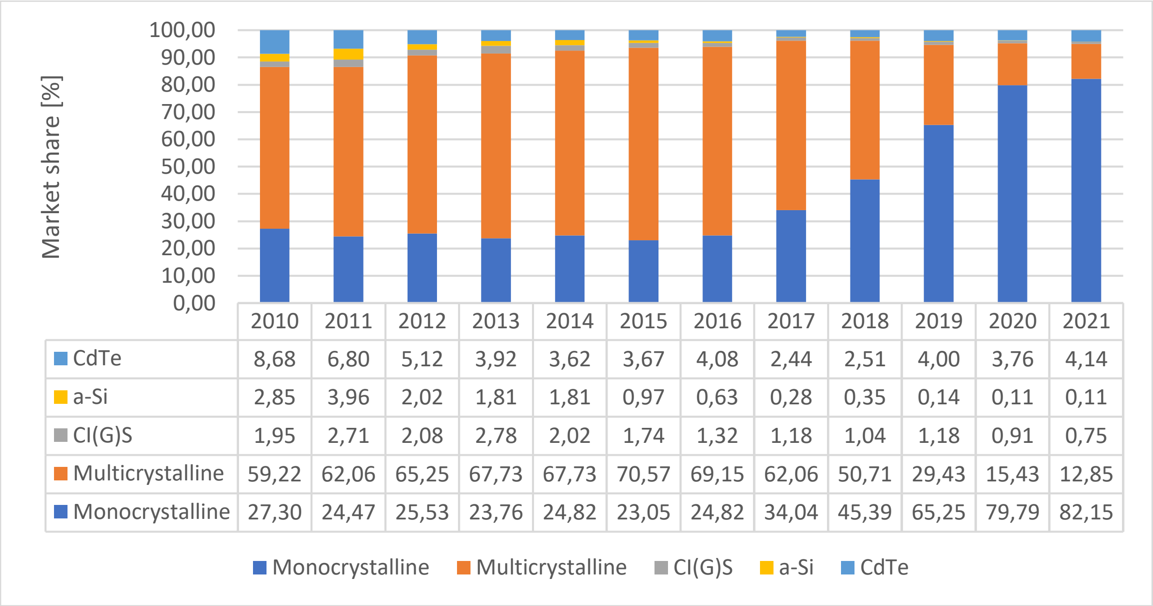
2. Second generation solar cells.

   This generation of cells has been developed mainly to reduce materials consumption and explore new materials compared to the first generation (11). These cells are formed by deposition of a thin layer of semiconductor material on a backing material made of glass, steel, or plastic (14). The most significant technologies in this generation are cadmium telluride (CdTe) cells, copper-indium-selenide (CIS) or copper-indium-gallium-selenide (CIGS) cells (also indicated as CI(G)S), and amorphous silicon (a-Si) cells (14) (11) (16) (17). CIGS technology is a modified version of CIS technology, replacing 15% of indium with gallium (18). Second generation technologies present a lower efficiency compared to first generation ones, but are potentially less expensive to manufacture thanks to the reduced number of steps required (14).

3. Third generation solar cells.

This generation has the aim of reducing the manufacturing costs and using more environmentally friendly materials (11). It includes a variety of technologies in the R&D[2] stage without a significant market share (16) (12). The main technologies included within this generation are dye sensitized solar cells (DSSC), organic photovoltaic (OPV) cells, and perovskite solar cells (11). The IEA mentions that OPV cells have created large research interest in recent years and are considered the fastest-advancing solar technology (14).

Figure 1 illustrates the share of worldwide modules production over the last decade for the different PV technologies (17).



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
CdTe	8,68	6,80	5,12	3,92	3,62	3,67	4,08	2,44	2,51	4,00	3,76	4,14
a-Si	2,85	3,96	2,02	1,81	1,81	0,97	0,63	0,28	0,35	0,14	0,11	0,11
CI(G)S	1,95	2,71	2,08	2,78	2,02	1,74	1,32	1,18	1,04	1,18	0,91	0,75
Multicrystalline	59,22	62,06	65,25	67,73	67,73	70,57	69,15	62,06	50,71	29,43	15,43	12,85
Monocrystalline	27,30	24,47	25,53	23,76	24,82	23,05	24,82	34,04	45,39	65,25	79,79	82,15

Figure 1: Share of PV modules production by technology (17).

As can be observed in Figure 1, since 2010 c-Si technologies held around 90% of the market, with the monocrystalline gaining share over the multicrystalline option in the last years, due to the demand for higher efficiency modules (14). The share of second-generation technologies reduced over time and makes up around 5% of the

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[2] R&D: Research and Development

total market in 2021, with CdTe technology accounting for over 80% of the second-generation market. Also, it is observed that third generation technologies are not included in Figure 1: they are still in the R&D stage and do not hold a significant market share (16) (12).

Now that a classification of solar technologies has been provided, the following subsection will present the evolution and the segmentation of the global PV installed capacity.

1.2.1. Global PV installed capacity and market segments

The global cumulative installed PV capacity grew by a CAGR[3] greater than 33% since 2010 (19), as shown in Figure 2.

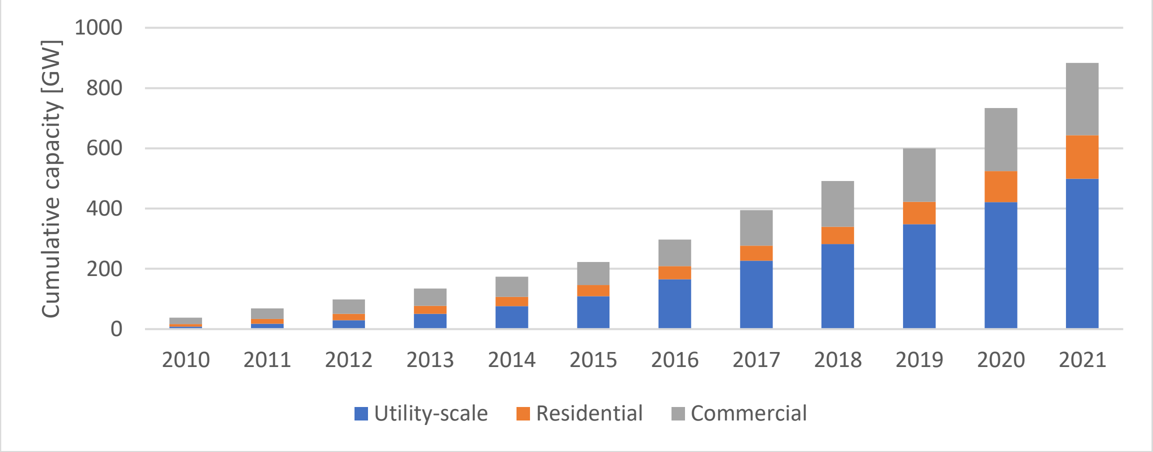

Figure 2: Global cumulative installed PV capacity by segment (19).

As can be observed in Figure 2, the global installed PV capacity can be divided into three segments. It is important to know that no fixed thresholds between segments exists, and for consistency with Figure 2 the definitions provided for the data plotted in Figure 2 are included in Table 1 (20).

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[3] CAGR: Compound annual growth rate

Segment	Size [kW]	Explanation
Residential	1-10	Rooftop system connected to the grid
Commercial	10-1000	Rooftop or ground-mounted system connected to the grid
Utility-scale	>1000	Ground-mounted system connected to the grid

Table 1: PV segmentation by size (20).

The segmentation provided in Table 1 refers to grid-connected applications. PV systems not connected to the main grid are defined as off-grid applications (15). It is observed that off-grid installations account for only 7.4 GW as of end 2021, representing less than 1% of the total PV installed capacity (19).
Considering a regional distribution, Figure 3 and Figure 4 provide the breakdown by country of the cumulative and additional installed capacity in 2021.

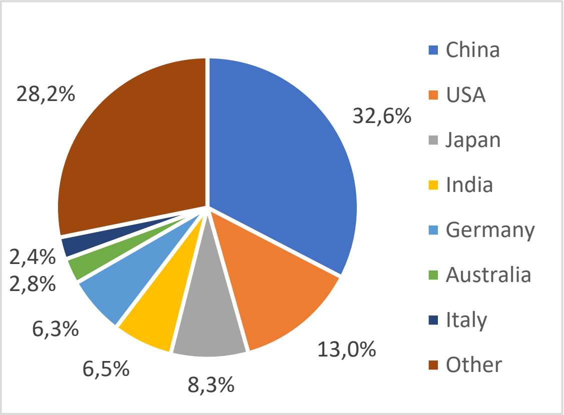

Figure 3: Cumulative PV capacity installed by country as of the end of 2021 (14).

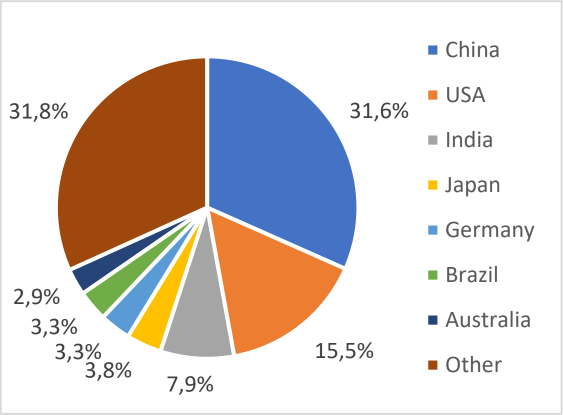

Figure 4: Additional PV capacity installed by country in 2021 (14).

As can be observed in Figure 3 and Figure 4, China is the market leader in solar PV since accounting for one third of worldwide cumulative and additional installed capacity in 2021. It is observed that Italy ranks as the seventh country worldwide for cumulative installed capacity, while it is outside the top ten countries for capacity addition in 2021, accounting for only 0.5% of the total increase (14).
In Figure 2, PV was segmented into residential, commercial, and utility-scale. This is not the only segmentation conceivable for PV systems. Another possible

segmentation considers the application. It is provided below an overview of some emerging PV applications (15):

- Building integrated photovoltaic (BIPV): it refers to the replacement of traditional building materials by materials containing PV cells (15).
- Floating PV: it refers to PV systems mounted on a floating structure (15).
- Agricultural PV: it refers to an application simultaneously using land to produce crops and generate PV electricity (15) (21).
- Vehicle integrated photovoltaic (VIPV): it refers to the integration of PV cells into the shell of a vehicle (15).

The segmentations provided demonstrate the large number of possible applications for PV technologies.

In the following subsection, it is presented an overview of the components of a ground-mounted or rooftop PV system.

1.2.2. Components of a PV system

A definition commonly applied in the literature consider a PV system as the sum of PV panels and the balance of system (BOS) (22) (23). Solar panels represent the core component of any PV system. A simple definition of solar panel suggested by the European Commission Report on PV systems is to define them as a combination of more solar cells in a weatherproof package (24). The BOS includes the components needed for the functioning of the PV system different than PV panels (25). It is observed that different scholars include different components within the boundaries of the BOS (26). The following BOS components are included by the IEA Methodological Guidelines on LCA of Photovoltaic (16) (27):

- Inverter: it is a device used to convert the direct current (DC) produced by PV panels into alternating current (AC) to be supplied to the grid (15).
- Mounting structure: it is the structure to support PV modules on a rooftop or on the ground. Ground-mounted racking system are typically steel-made, coated, or galvanized to protect from corrosion (28).
- Cabling: it includes cables to transport the energy generated from modules to the inverter (24).

After this brief introduction to PV technologies, the following section aims at presenting the environmental sustainability considerations related to PV technologies.

1.3. The environmental sustainability of PV technologies

PV technologies are a powerful tool to tackle climate change: they can help in the decarbonization of the power system (15). As a matter of fact, the global average carbon intensity of electricity generation is equal to 475 gCO_2/kWh in 2019, while the emission of a PV plant can reach as low as 15 gCO_2/kWh (15). Another way to demonstrate the positive environmental impact of PV technologies is given by the estimate of the CO_2 equivalent ($CO_{2\text{-eq}}$) emissions avoided by solar PV. $CO_{2\text{-eq}}$ is a metric computed by converting the emissions of various greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), into the equivalent CO_2 emissions on the basis of their global warming potential (29) (30). Assuming the worldwide installed PV capacity to be replaced by the grid mixes of the country where it is located, it is computed that 1060 Mton of $CO_{2\text{-eq}}$ are avoided annually thanks to PV technologies (14). This represents over 3% of the total energy sector emissions in 2021 (14) (31). Despite the positive environmental effect generated by PV technologies, it is fundamental to consider also their negative environmental externalities. Emissions from PV manufacturing quadrupled to almost 52 Mton of CO_2 over the last decade and accounted in 2021 for 0.15% of global energy-related CO_2 emissions (32). The driver behind this growth are the sevenfold production increase and the production capacity moving to China, as shown in Figure 5 (32).

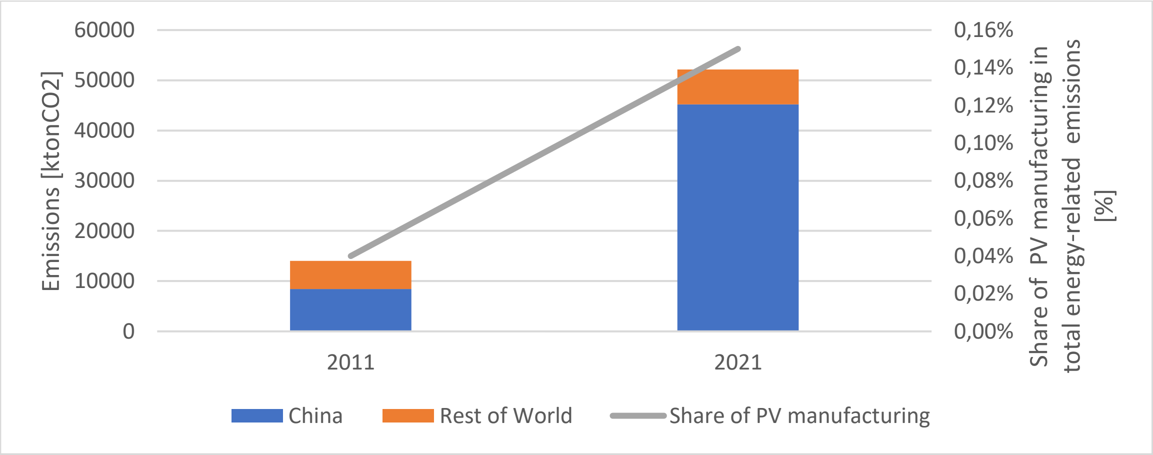

Figure 5: CO_2 emission from PV manufacturing globally and share of PV manufacturing in total energy-related emission (right axis) (32).

A key critical point related to the environmental sustainability of PV technologies is represented by the fact that most of solar panel manufacturing takes place in China, a country characterized by a high emission intensive energy mix: consequently, the resulting life cycle emissions of a PV panel manufactured in China are way higher than the case in which the same panel would have been manufactured in a country with a less polluted electricity system (32). As shown in Figure 5, China is responsible for almost 90% of worldwide emissions across PV modules manufacturing supply chain (32).

After this short introduction showing that the use of PV technologies brings environmental benefits, while their production has an impact in terms of pollutant emissions, the following subsection presents the multiple environmental impact categories associated to PV technologies.

1.3.1. The environmental impact of PV technologies

It is observed that different scholars consider different categories of environmental impact associated to PV technologies (33). In line with the reviews from Tawalbeh et al. (33) and from Turney and Fthenakis (34), analyzing the environmental impact categories related to PV systems covered in the literature, the categories considered in the current subsection are land use, air pollution and climate change, human health, water usage.

1.3.1.1. Land use

Solar power systems are considered to have a higher energy land use intensity compared to other renewable energy technologies (33). Land requirements and competition with agricultural activities bring to the consideration that deserts and no cropping areas represent the ideal locations to install utility-scale PV systems (33). An important consideration needs to be done for rooftop PV systems, that can be considered to have no impact on land occupation since the land was already occupied (16). As shown by Figure 6, despite the larger impact with respect to other renewable energy technologies, solar PV presents a land occupation lower if compared to coal power plants, because of the huge land requirements of the initial stages of coal extraction from mines (16).

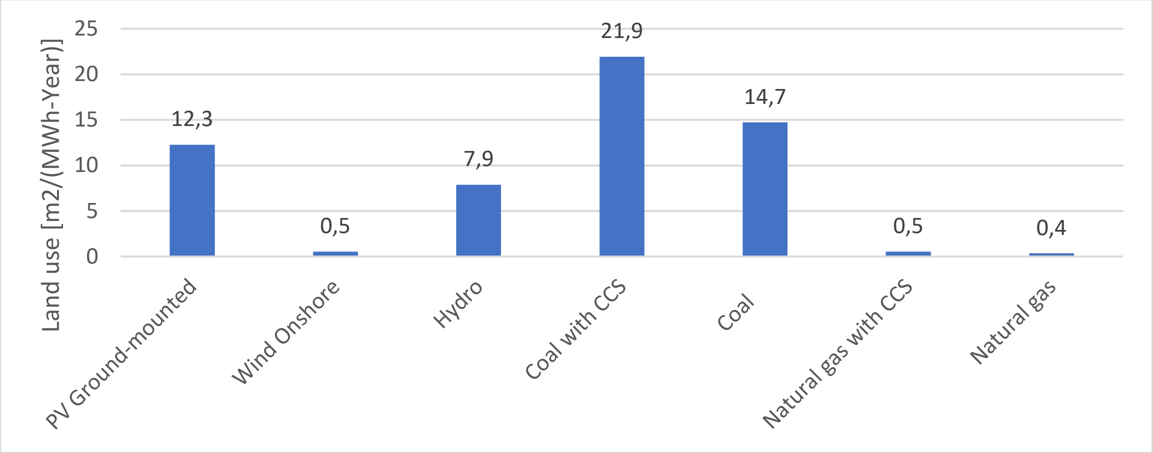

Figure 6: Land occupation for selected technologies (16).

Some possibilities to reduce the land occupation include the reduction of the spacing between rows of PV modules (33). Another possibility is the installation of hybrid power systems: a hybrid solar-wind system can reduce the land requirement from 4 to 1 acre per MW (35). Another out-of-the box solution is the installation of floating PV systems (15).

1.3.1.2. Air pollution and climate change

PV systems are considered to produce negligible emissions during operations (36). Nevertheless, to have a proper evaluation of their impact, all phases of the life cycle from manufacturing to end-of-life must be included. The manufacturing phase is the largest contributor to the total emissions, evaluated to account for up to 90% of CO_2 emissions over the life cycle (33). The dominant role of the manufacturing phase on the life cycle emissions is indeed confirmed by multiple scholars, such as Eskew et al. (37) and Ludin et al. (38). An important consideration is that the life cycle carbon footprint [$gCO_{2\text{-eq}}$/kWh] of PV technologies is one order of magnitude lower than that of fossil fuel power generations, as shown by Urbina (16) and also by the NREL[4] (39). Given the lower emissions compared to traditional power generation technologies, PV is considered a powerful tool to fight climate change (15).

1.3.1.3. Human health

The first impact on human health to be presented in the current paragraph is the exposure to hazardous materials (34). The manufacturing of PV cells emits many heavy metals, the major being nickel, mercury, arsenic, cadmium, chromium, and lead (33). The adverse effects on human health associated with exposure to heavy

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[4] NREL: National Renewable Energy Laboratory

metals include neurotoxic and carcinogenic actions (40). Nevertheless, it is observed that the emissions of heavy metals due to PV are lower if compared to other power technologies, such as fossil fuel-based generation and wind energy (41). For example, it is observed that solar power emits 50 to 1000 times less mercury compared to traditional generation technologies (34). Similarly, it is evaluated that electricity produced from CdTe modules emits 100 to 300 times less cadmium than coal power generation (34). Hazardous materials also include the several chemicals employed in the production processes of PV technologies, such as hydrochloric acid, nitric acid, and isopropanol (33). Most of these chemicals are inflammable, corrosive, toxic, and carcinogenic, thus requiring a proper handling to reduce their threat on human health (42).

The second impact on human health to be presented is the noise pollution. Noise is defined by the World Health Organization (WHO) as an unwanted sound, and it is considered a type of pollution due to its impact on human health (33). PV technologies do not produce significant noise during the operation phase (43). Instead, during the installation phase, noise is generated by machineries and workers on site, potentially harming people as well as wildlife (33). Nevertheless, it is observed that noise pollution from PV installation phase is lower if compared to the installation of other renewable energy technologies such as wind power or biomass (33).

The third impact on human health presented is the visual pollution. The visual impact of PV appears to be a problem mainly raised by local communities or environmental activists (33). The negative impact depends on the areas covered and the location: utility-scale projects in rural areas are considered to have a higher visual impact than systems installed on rooftops or BIPV (33). The measures to limit visual pollution include the proper selection of the installation site, the enhancement of the integration of PV panels in the facades of buildings, and the engagement of the public in the early planning phases to gain public acceptance (33) (43).

1.3.1.4. Water usage

The manufacturing process is responsible for most of the water consumption during the life cycle of PV technologies (33). Water is also consumed in the operational phase for cleaning purposes (16). Jin et al. (44) as well as Fthenakis and Kim (45) demonstrated that PV technologies present one of the lowest water footprints during the life cycle across power generation technologies, as shown in Figure 7.

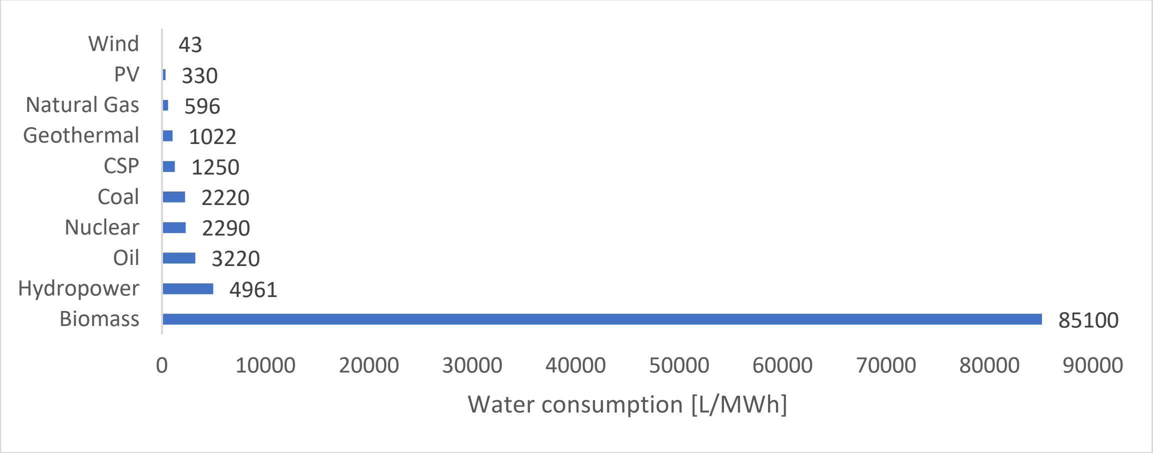

Figure 7: Median of water consumption over the full life cycle for selected technologies (44).

After this introduction to the environmental sustainability of PV technologies, the following subsection will focus on the importance of the Life Cycle Assessment methodology in relation to PV technologies.

1.3.2. The importance of the LCA for PV technologies

The previous paragraphs presented the multiple environmental impact categories associated with PV technologies. Life Cycle Assessment (LCA) is considered the best framework to evaluate the environmental impact of products, processes, and services and an indispensable tool in supporting decisions towards a more sustainable planet (46). LCA is defined and regulated by standards of the International Organization for Standardization (ISO) (16) (27). However, LCA leaves the individual practitioners with multiple choices that can significantly affect results (27). Thus, for LCA applied to PV technologies, IEA provides methodology guidelines to increase consistency and quality of results (27). In the review artcile from Gerbinet et al. (47), it is stated that the first LCA studies on PV technologies appeared in the 1970s. From that moment, hundreds of LCA studies have been conducted on PV technologies, and a wide range of results have been obtained, due to the differences in the assumptions adopted (48).

The current thesis focuses on the LCA of PV technologies.

LCA of PV technologies is considered a relevant topic for multiple reasons. First, the expected increase in PV installation in the next decades demonstrated at the beginning of the current chapter (1). Second, the multiple environmental impact categories associated to PV energy and the need to tackle them: it is cited as an example the importance of reducing GHG emissions to be consistent with the objectives of Paris Agreement (3). Third, given the technological improvements in PV technologies and the shift in manufacturing locations, it is important to complete

updated LCA studies (48).
The following section will present the LCA methodology.

1.4. The LCA methodology

Life Cycle Assessment (LCA) is an internationally standardized methodology considered the best framework to evaluate the environmental impact of products, processes, and services (46). The increasing importance assumed by LCA is given for example by the fact that the European Commission has put in place the European Platform on LCA to support the use of LCA in business and policy contexts, and LCA is already the backbone of several European environmental policies (46). LCA is used in numerous companies to evaluate the environmental impact of their products and services, to find room for improvement, and in communication with governmental bodies (49). ISO 14040 and ISO 14044 are the two key norms defining the LCA (50) (27). The ISO 14040 defines LCA standards and framework, while operational guidelines are covered by the ISO 14044 (16) (46). LCA is defined by the ISO 14040 as the 'evaluation and compilation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle' (51) (46). In line with these standards and guidelines, the European Commission released the International Reference Life Cycle Data System (ILCD) handbook, to provide further guidance for consistent and quality assured LCA studies, since it is observed that ISO standards leaves the individual practitioner with a range of choices that can affect the legitimacy of results (46) (50).

After this brief introduction to the norms defining the LCA methodology and its increasing diffusions in the business and public contexts, the following subsection will present the steps composing an LCA analysis.

1.4.1. The steps composing an LCA analysis

LCA is standardized by the International Organization for Standardization and is divided into four main phases (51) (46) (52):

1) Goal and scope definition phase.
2) Life cycle inventory (LCI) phase.
3) Life cycle impact assessment (LCIA) phase.
4) Life cycle interpretation phase.

Each phase will now be presented individually.

1.4.1.1. Goal and scope definition phase

In this phase the aims of the study are defined, the reasons for carrying out the analysis as well as the intended audience (46) (51) (52). The main methodological choices are stated in this step, namely the definition of the functional unit, the identification of the system boundaries, the impact categories studied, and the life cycle impact assessment models used (46) (51) (52). Other aspects that should be addressed in this phase, according to the ILCD handbook from the European Commission, include the identification of the limitations in the methodology used, the identification of the commissioner of the study and other relevant actors, the definition of the deliverables and the intended application (50).

1.4.1.2. Life cycle inventory phase

This phase involves the collection of data and the computation of inputs and outputs associated to the system under study (51) (46) (52). Inputs and outputs include energy, materials, wastes and emissions to air, water, and soil (46) (52). It is important to notice that the LCI phase is considered an iterative process: as data are collected, more is discovered about the system under study, and new requirements and limitations may be consequently identified (51) (46). The LCI phase is considered the one requiring more time and resource (50).

1.4.1.3. Life cycle impact assessment phase

In this phase inventory data are associated to environmental impact categories and indicators (52) (46) (51). As shown in Table 2, this phase includes four sub-steps: classification, characterization, normalization, weighting (52) (50).

Step	Description
Classification	Assigning the input and output of material or energy to the relevant impact to which they contribute.
Characterization	Computation of the contribution of each input and output to their respective categories and aggregation of the contribution for each category.
Normalization	Results of the LCIA are here normalized. Normalization is an optional step under ISO 14040 standard.
Weighting	Weighting consists in assigning quantitative weights to impact categories. Weighting is an optional step according to ISO 14040 standard.

Table 2: Steps composing the LCIA phase (52).

1.4.1.4. Life cycle interpretation phase

In this phase results from the LCI and LCIA phases are interpreted in compliance with the stated goal and scope (46) (51). According to ISO standards, this phase should (53):

- Identify significant issues.

The objective of this step consists in structuring and analyzing results to identify the significant issues (50). These include the life cycle stages or processes as well as the methodological choices, such as the assumptions, the inventory data, and the LCIA methodology used, that have the strongest influence on results (50) (53).

- Evaluate results.

The objective of the evaluation stage is to enhance confidence in the results of the LCA study (53). It is performed to establish foundations to draw conclusions in the subsequent step (50). If any information judged relevant for the interpretation is missing, the previous LCI and LCIA phases should be revisited (53). The use of three techniques is to be considered (53). First, a completeness check, to ensure that all data necessary for the interpretation are available and complete (53). Second, a sensitivity check, to evaluate the reliability of results with respect to uncertainties in the data, modeling choices, and assumptions (53) (50). Third, a consistency check to determine whether assumptions, methodologies, and inventory data have been applied consistently with the goal and scope (53) (50).

- Reach conclusions, explain limitations, and provide recommendations.

Conclusions shall be derived in accordance with the stated goal and scope in an iterative way from the identification of significant issues and the evaluation of results (50). Limitations within the goal and scope of the LCA must be listed in this phase and it is to be evaluated for each of them the magnitude of their effect on conclusions (50). Recommendations should be based on the conclusions of the study and should represent their logical consequences (53).

The current chapter provided an overview of solar PV and of LCA methodology and presented the relevance of the topic tackled in the thesis. The following chapter will present the review of the existing literature on LCA of PV technologies.

2 Literature review

2.1. Process followed

A literature review is carried out to analyze the existing literature on LCA of PV technologies and identify research gaps. The first step consists in an advanced query search on SCOPUS database, using a combination of the words 'LCA' and 'PV' or similar. The following query is used:

Title-Abs-Key (("LCA" OR "Life cycle assessment" OR "Life Cycle Analysis") AND ("PV" OR "Photovoltaic energy" OR "Photovoltaic" OR "PV energy"))

The research query generates a total of 1446 documents.

The second step consists in an initial filtering of the sample obtained. Four criteria are used:

1) Documents published before 2010 are excluded.
2) Documents in a language different than English are excluded.
3) Documents in a subject area different than 'Energy', 'Environment', and 'Business, Management and Accounting' are excluded.
4) Documents that are books or book chapters are excluded. Accordingly, the literature review will focus on papers.

The second step leads to the selection of 1004 papers.

The third step consists into a title analysis on the sample of 1004 documents.
The criteria used to filter are the following:

- Papers focusing on topics different than LCA of solar energy.

Contributions focusing on topics different than LCA of solar energy are excluded. This criterion leads to the exclusion of 582 contributions. For example, papers performing an LCA on storage systems, papers performing an LCA on solar-based hydrogen production, as well as papers performing an LCA on geothermal power plants or on wind farms are excluded.

- Papers focusing on LCA of solar energy different than PV.

Contributions focusing on LCA of solar energy different than PV are excluded. This criterion leads to the exclusion of 74 documents. For example, contributions performing an LCA on solar thermal systems or on concentrating solar systems are excluded.

- Papers focusing on social LCA of PV energy.

Contributions focusing on the social LCA of PV energy are excluded. Only one contribution is excluded with this criterion.

- Papers with a title judged not clear.

Contributions with a title judged not clear enough to pass to the following step are excluded. 8 documents are excluded with this criterion. For example, it is excluded a document titled ‘IOP Conference Series: Earth and Environmental Science’, as well as a document with the title ‘2014 1st International Conference on Green Energy, ICGE 2014’.

The title analysis leads to the selection of 339 documents.

The fourth step consists in an abstract analysis. The exclusion criteria used to complete the filtering are the following:

- Papers performing analysis at a level different than a PV system.

Papers performing an LCA at a level different than a PV system are excluded. 92 documents are excluded with this criterion. Examples of contributions excluded are those performing an LCA at a level bigger than a PV system, such as on microgrids, as well as papers proposing analysis at the level of a factory or of the PV industry. Also, papers performing an LCA at a level smaller than a PV system are excluded. Examples of contributions excluded are those completing an LCA on the components of a PV system, such as tracking devices, as well as a contribution performing an LCA on the machine to mechanically recycle PV modules.

- Papers not focusing on LCA of PV technologies.

Papers judged as not focusing on LCA of PV technologies are excluded. 65 papers are excluded with this criterion. For example, papers focusing on the life cycle costs of PV systems are excluded, as well as a paper presenting the effect of the substitution of coal-based plants with PV under Chinese feed-in-tariff policies, and a document analyzing the economic benefits of BIPV in Taiwan.

- Papers focusing on future oriented LCA studies.

Papers focusing on the evaluation of the future impact of PV technologies are excluded. 14 contributions are excluded with this criterion. For example, it is excluded a contribution presenting an evaluation of the environmental impact of third generation PV technologies in 2050, as well as a paper published in 2014 proposing an evaluation of the impact of PV technologies in 2020.

- Papers focusing on the statistical analysis of previous studies.

Papers focusing on the statistical analysis of previous studies are excluded. This criterion leads to the exclusion of 8 documents. For example, it is excluded a contribution performing a meta-analysis on the values of the energy payback time computed from a total of over 200 previous studies, as well as a paper focusing on the meta-analysis of the greenhouse gases emissions of first-generation PV technologies estimated from a sample of 397 studies.

- Papers focusing on the effect of a specific parameter.

Documents performing an LCA focusing on the effect of a specific parameter are excluded. 7 documents are excluded with this criterion. For example, it is excluded a paper modeling the effect of operating temperature on life cycle greenhouse gas emissions, as well as two documents focusing on the evaluation of the effect of modules degradation on greenhouse gas emissions.

- Papers performing a hybrid LCA.

Papers performing a hybrid LCA are excluded. Hybrid LCA is defined as combining process based LCA and economic input-output analysis (54) (55). 2 contributions are excluded with this criterion.

- Papers judged not eligible for other reasons.

Documents judged not eligible for the full text analysis for other reasons with respect to the criteria mentioned above are excluded. 22 documents are excluded with this criterion, including 4 documents where the full text is not available on SCOPUS and 18 documents judged not eligible for the full text analysis. For example, it is excluded a paper assessing the impact in terms of water consumption of large-scale PV systems, as well as a paper focusing on the comparison of lead emissions of perovskite PV with respect to the U.S. electricity mix, and a contribution focusing on the computation of the 'greenhouse gas emissions profit' of solar PV systems with respect to conventional power generation.

The abstract analysis leads to the selection of 129 papers.

The 129 papers are analyzed using a full text analysis, with the objective of highlighting research gaps. Figure 8 provides a graphical representation of the process leading to the selection of the relevant literature.

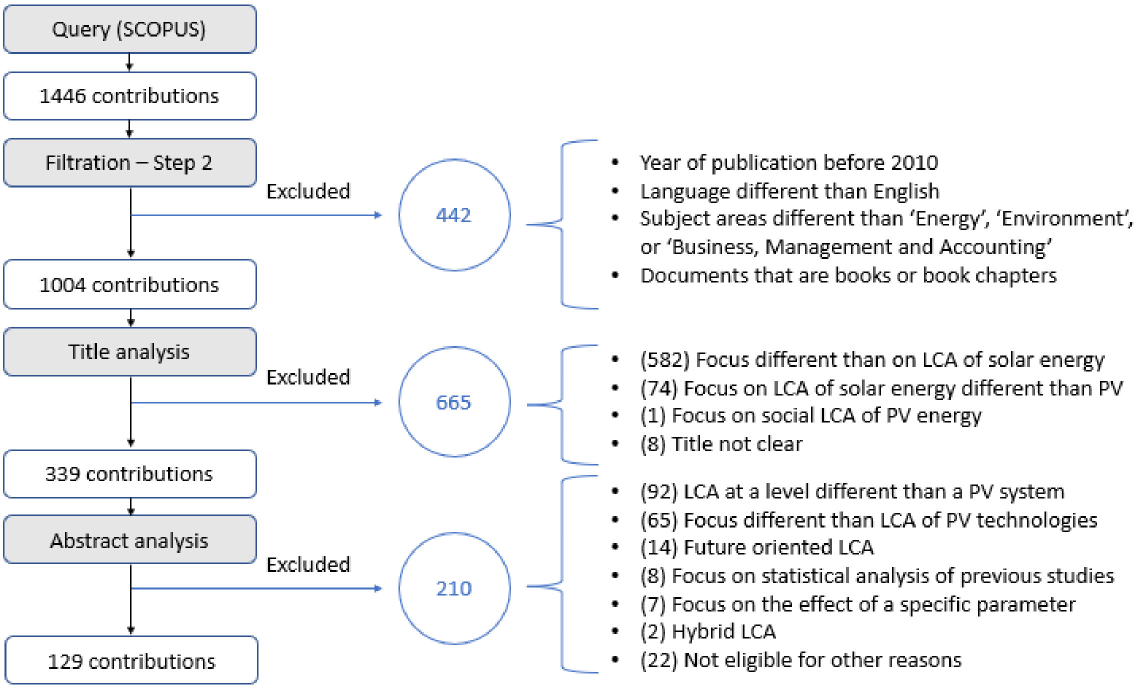

Figure 8: Process of selection of the relevant contributions (Own production).

2.2. Full text analysis

The full text analysis is completed with the usage of a table to classify the information encountered in the literature. The table is provided in Appendix A.1. The composition of the table is the following:

- Introductory information.

The objective of this section of the table is to univocally identify and classify the contributions analyzed. The information included are: author, year of publication, title, type of contribution.

- Methodological aspects.

The objective of this section of the table is to analyze the main methodological choices applied in the LCA analysis. The dimensions investigated are the following: functional unit, life cycle inventory, life cycle impact assessment, boundaries and phases, software, sensitivity analysis.

- PV system hypothesis.

The objective of this section of the table is to identify and analyze the most important assumptions regarding the PV system analyzed. The dimensions considered are the following: modules manufacturing location, BOS manufacturing location, installation location, modules generation and technology, installation configuration, emerging PV applications, storage system.

- PV technical parameters.

The objective of this section of the table is to analyze the key PV technical parameters applied in the contributions analyzed. The parameters included are the following: module efficiency, irradiation, lifetime.

Now that the structure of the table has been provided, the next step consists in presenting the findings from the literature review. The presentation of the findings follows the order of the table.
Furthermore, Subsection 2.2.5 will cover the modeling approaches adopted in the contributions analyzed to complete the LCA.

2.2.1. Introductory information

The current subsection presents the years of publication and the types of the contributions analyzed.

2.2.1.1. Year of publication

Figure 9 shows the temporal distribution by year of publication of the contributions analyzed.

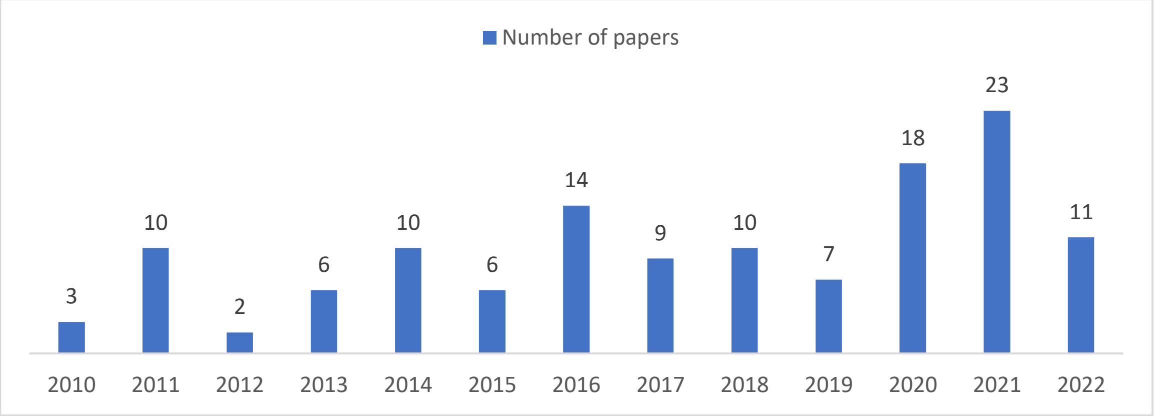

Figure 9: Contributions analyzed by year of publication (Own production).

As can be seen from Figure 9, the years of publication spread from 2010 to 2022, with 98 out of 129 contributions published from 2015 onwards.

2.2.1.2. Type of contribution

The classification of documents provided by SCOPUS is used to segment the sample analyzed.
The sample is composed of:

- 108 journal articles.
- 16 reviews.
- 5 conference papers.

The segmentation provided demonstrates the diversity of sources considered in the full text analysis.

2.2.2. Methodological aspects

The current subsection examines the main methodological choices applied in the LCA studies analyzed. This is fundamental to grasp a better understanding of the choices made by other scholars and highlight research gaps. The analysis covers the functional unit considered, the life cycle inventory, the life cycle impact assessment, the boundaries and the phases characterizing the system analyzed, the software applied, and the inclusion of sensitivity analyses.

2.2.2.1. Functional unit

As presented in Paragraph 1.4.1.1, LCA guidelines state the need of defining the functional unit (FU) applied in the study. Figure 10 shows the most frequently applied functional units in the literature analyzed and their respective number of appearances.

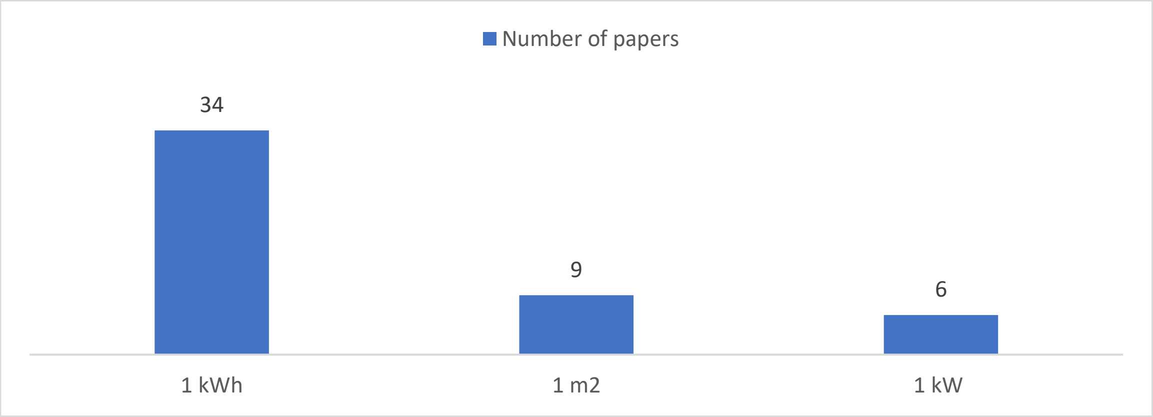

Figure 10: Most frequently applied functional units in the literature analyzed (Own production)

The analysis of the literature shows that the most applied FU is defined as '1 kWh' of generated electricity: it is encountered in 34 out of 129 contributions. Other commonly applied functional units are related to the area (1 m^2) or to the power (1 kW). In addition, it is observed that a FU related to the weight is a common choice in papers focusing on the end-of-life phase. For example, Ansanelli et al. (56) analyze a recovery process for silicon-based modules and apply as functional unit 24 ton of end-of-life crystalline silicon (c-Si) PV modules. Similarly, Latunussa et al. (57) as well as Dias et al. (58) perform an LCA on a recycling process for silicon modules, applying as FU 1000 kg of c-Si modules. To conclude, it is important to mention that in 45 contributions the FU is either not specified or the concept of FU is not applicable, as for example in case of review papers.

2.2.2.2. Life cycle inventory

As presented in Paragraph 1.4.1.2, the life cycle inventory phase involves the collection of data and the computation of inputs and outputs associated to the system under analysis. The current paragraph analyzes the sources of data employed in the contributions analyzed. Three categories of data sources are identified as the most frequently used:

- Ecoinvent: cited as a source of data in 78 papers.

  Ecoinvent is the leading LCI database, containing around 18000 life cycle inventory datasets updated annually (59). An example of a contribution falling within this category is the one from Laleman et al. (60), applying the Ecoinvent database to carry out an LCA on residential PV systems in regions with a low solar irradiation.

- Literature: cited as a source of data in 75 papers.

  Applying the literature as a source of data consists in collecting data from other papers. An example falling within this category is the paper from Lima et al. (61), presenting an LCA on PV systems located in Brazil and sourcing data from other scholars.

- Industry data: cited as a source of data in 40 papers.

  This category includes data from manufacturers, interviews to industry experts, and surveys to companies. Examples of contributions included in this category are given by Held and Ilg (62), stating to use data from First Solar's production plant, as well as by Santoli et al. (63), collecting information from companies specialized in PV modules assembly.

Other examples of commonly applied data sources are laboratories measurements (cited 10 times), direct measurement from field visits (cited 5 times), and GABI professional database (cited 4 times). The latter refers to a professional LCI database including over 17000 datasets (64). Data from laboratory measurements are often applied in studies analyzing emerging technologies, such as the one from Błaszczyk et al. (65) evaluating the environmental performances of dye-sensitized solar cells. Furthermore, it is observed that multiple categories of data sources are often adopted at the same time: 81 out of 129 contributions use more than a single category of data sources to compile the life cycle inventory. An example is given by Üçtuğ and Azapagic (66), mentioning as sources the literature, industry data, and Ecoinvent.

The data sources used to compile the life-cycle inventory can be segmented into primary and secondary data (67). Primary data refer to directly measured data representative of specific facilities, including for example data from manufacturers and measurement from field visits (67). Secondary data are not directly measured, but they are sourced from a third party, for example databases or previous literature (67).

Figure 11 provides the number of contributions applying the different data source (primary, secondary, or a combination of both).

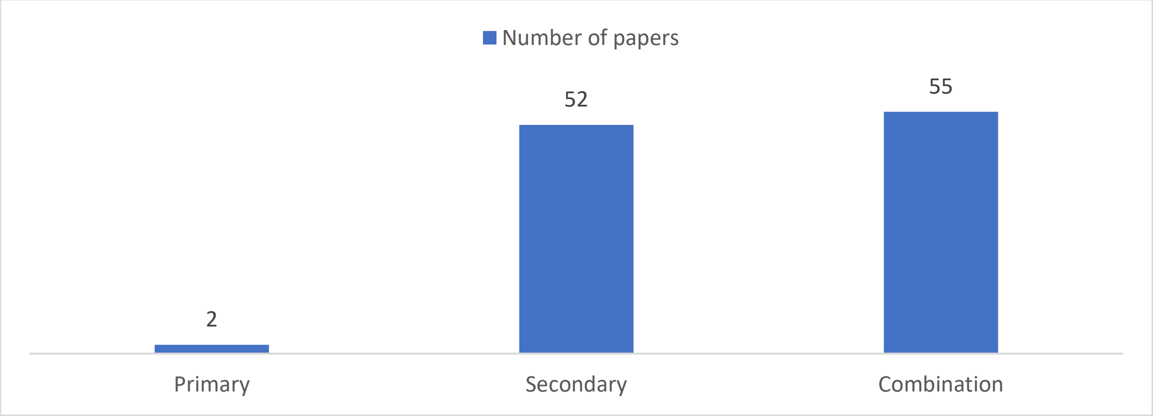

Figure 11: Types of data sources used in the literature analyzed (Own production).

Figure 11 shows that 52 out of 129 contributions are not using primary data. The limited usage of high-quality primary data is considered a limitation of the literature. The recent review from Muteri et al. (12) observes a shortage of primary data in the literature. Resalati et al. (68) observe that gathering high quality data has proven difficult for LCA practitioners, for example due to manufacturers' confidentiality agreements. As a matter of fact, the different qualities of inventory data represent an issue making comparison among LCA studies difficult (69). In order to improve data accuracy, governments and companies in the PV industry should collaborate to foster data collection and monitoring across factories (70).

After having analyzed the type of sources applied in the literature, it is important to evaluate whether the data used are updated. As demonstrated at the beginning of the paragraph, Ecoinvent is the data source applied with the highest frequency in the sample analyzed. In order to have a proxy for the usage of updated data, it is compared the year of publication of papers specifying the Ecoinvent version applied and the corresponding year of release of the version (71). An example is provided to better understand: the paper from Pamponet et al. (72) was published in 2021, but the Ecoinvent version used is the 3.5, released in 2018 (71). Consequently, the publication year considered in Figure 12 is 2021, while the Ecoinvent version year is 2018. The results obtained are plotted in Figure 12.

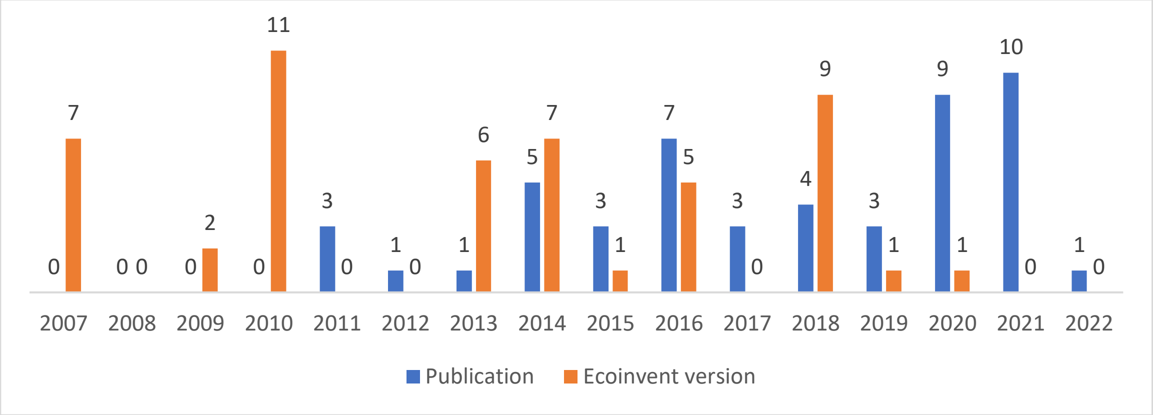

Figure 12: Comparison between the year of publication of papers and the version of Ecoinvent applied (Own production).

Figure 12 shows that older versions of Ecoinvent are the most frequently used, even if most papers have been published more recently. This suggests a limited usage of updated inventory data in the literature. To confirm the usage of outdated data sources even when the source of data is represented by the literature, the following examples are provided:

- Rashedi and Khanam (73) include seven sources from the literature to compile the life cycle inventory. Even if the paper was published in 2020, the most recent of the cited sources dates to 2014, and five sources have been published before 2010.
- In the paper from Ramhan et al. (36) published in 2019, it is applied the average of values from a source published in 1995 and a source published in 2013 to define the cumulative energy demand to manufacture PV modules.

The results obtained suggest that a limitation of the current literature is the limited usage of updated inventory data. The observation is confirmed by Muller et al. (74), mentioning that PV LCA studies are often based on outdated inventories. As a matter of fact, the need for updated inventory of PV modules is mentioned by Antonanzas et al. (75). The gap is considered relevant, since the use of outdated inventory data can bring to divergent conclusions for scholars and decision makers (76), given the discrepancies between databases and real-world data, while technologies are quickly evolving (77).

2.2.2.3. Life cycle impact assessment

As presented in Paragraph 1.4.1.3, in the LCIA phase inventory data are associated to environmental impact categories and indicators. The analysis of the literature suggests that four metrics are commonly applied to evaluate the impact of PV technologies: global warming potential (GWP), cumulative energy demand (CED), energy payback time (EPBT), CO_2 payback time (CO_2PBT). As a matter of fact, in the review from Ludin et al. (78) it is observed that CED, EPBT, and GWP are the most frequently used metrics in comparative LCA studies of PV systems since 2010, while Li et al. (79) define EPBT and CO_2PBT as the two most widely used environmental indicators for PV systems.

The GWP is a measure of the effect on global warming of a PV system over its life cycle (78). It is usually expressed as $\frac{gCO_{2-eq}}{Functional\ Unit}$ (80). Given that, as demonstrated in Paragraph 2.2.2.1, the most applied functional unit is the kWh of electricity generated, GWP is often expressed as $gCO_{2\text{-eq}}$/kWh. Examples of contributions applying such a unit of measure are those from Kim et al. (81) and Raugei et al. (82).

The CED is a measure of the primary energy consumed during the life cycle of the PV system (78). It is usually expressed in MJ (60), as in Nordin et al. (83) and in Akinyele et al. (84).

The EPBT is a measure of the time needed for an energy system to generate the same amount of energy that was consumed in the full life cycle of the system (81) (80). It is usually expressed in years, as can be observed in the reviews from Peng et al. (85) and Wu et al. (86).

The CO_2PBT is a measure of the time needed to offset the $CO_{2\text{-eq}}$ emissions generated over the life cycle of the system by the $CO_{2\text{-eq}}$ emissions reduction generated by the system itself (80) (83). Thus, it can be defined as the ratio of the total $CO_{2\text{-eq}}$ emissions generated over the life cycle of the PV system to the emissions avoided by replacing the local electricity mix with the PV system (87). It is usually expressed in years, as for example in the papers from Antonanzas et al. (75) and Li et al. (79).

Figure 13 shows the number of contributions including each of the four metrics.

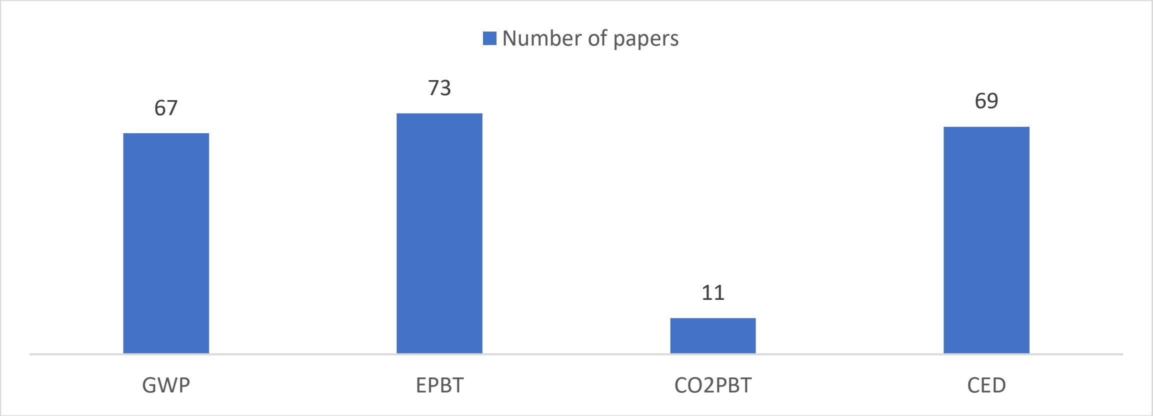

Figure 13: Appearances of selected metrics in the literature analyzed (Own production).

It is observed that the CO_2PBT is included less frequently than the other three metrics. The findings confirm the observation from Ludin et al. (78): GWP, EPBT, and CED are the most applied metrics in LCA of PV technologies. Furthermore, it is evaluated that only 3 out of 129 papers include all the four aforementioned metrics, namely Antonanzas et al. (75), Nordin et al. (83), and Lima et al. (61). The importance of using multiple indicators is mentioned in the literature analyzed. Rashedi and Khanam (73) observe that a common limitation of the studies analyzed is the fact of addressing a limited set of indicators. Chatzisideris et al. (88) highlight the importance of covering multiple environmental impact indicators, and mention as a future improvement for LCA practitioners the inclusion of results for more environmental issues. The limited usage of a combination of metrics evaluating more than one environmental problem is considered a relevant gap of the literature since the combination of more indicators can help in identifying trade-offs and taking more informed decisions (88).

It is important to notice that the IEA Methodology Guidelines for PV LCA indicate to use a larger set of indicators to evaluate the environmental impact, and not only energy and emissions related indicators (27). This includes indicators to measure the impact on climate change, ozone depletion, human toxicity, acidification, eutrophication, land, and water use (27). Accordingly, it is observed that different impact assessment methodologies are applied in the literature. Figure 14 shows the three methodologies adopted with the highest frequency in the sample analyzed and their respective number of appearances.

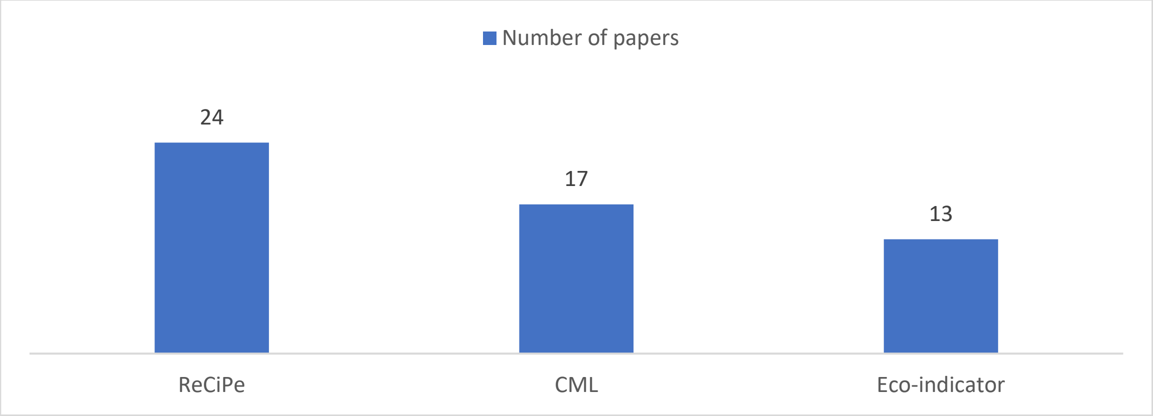

Figure 14: Most frequently applied impact methodologies in the literature analyzed (Own production).

The three methodologies appearing with the highest frequency are ReCiPe, CML, and Eco-indicator. Eco-indicator assessment method was developed in 1999 and defines the environmental impact according to its effect on three endpoint indicators: human health, ecosystem quality, and depletion of non-renewable resources (60). It is important to define that endpoint indicators focus on a higher aggregation level, such as 'human health', while midpoint indicators focus on a single environmental problem such as 'terrestrial acidification' (89). CML is an impact assessment method restricting the modeling to the early stages of the cause-effect chain to limit uncertainties (90), and grouping results in midpoint categories such as global warming potential, abiotic depletion potential, acidification potential, eutrophication potential, human toxicity potential, freshwater aquatic ecotoxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, ozone depletion potential, and photochemical oxidation potential (91) (90). ReCiPe methodology has been developed based on its predecessors CML and Eco-indicator (92), and provides results both at the midpoint and endpoint levels (93), as shown by Table 3.

Midpoint impact categories	Endpoint impact categories
Particulate matter, tropospheric ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity, global warming, water use	Damage to human health
Freshwater ecotoxicity, freshwater eutrophication, tropospheric ozone, terrestrial ecotoxicity, terrestrial acidification, land use/transformation, marine ecotoxicity	Damage to ecosystems
Mineral resources, fossil resources	Damage to resource availability

Table 3: Impact categories included in ReCiPe methodology (89).

Other impact assessment methodologies appearing less frequently in the literature analyzed include Impact 2002 (used 8 times) and TRACI (used 9 times). The impact categories included in the two mentioned methodologies are similar to those of ReCiPe.

2.2.2.4. Boundaries and phases

Considering the boundaries of the system analyzed, two definitions are often adopted: cradle-to-grave and cradle-to-gate. A cradle-to-grave perspective is adopted when a complete PV life cycle is considered (88) (94) (81), from raw materials extraction to end-of-life (88). The other option is the so-called cradle-to-gate perspective: it is defined as covering the stages from the production to the delivery of the product (16). In case of a PV system, a cradle-to-gate perspective usually excludes the operation and maintenance (O&M) and end-of-life phases (16). Examples of papers applying a cradle-to-gate perspective are given by Anctil et al. (95) and Tsang et al. (96).

Now that the definition of the boundaries of the system analyzed has been provided, the phases in which a cradle-to-grave LCA study applied to PV systems is usually divided are analyzed. Firstly, it is presented the subdivision provided by the IEA Methodology Guidelines (27):

- Product stage.

  This phase includes the supply of energy and raw materials as well as the manufacturing of modules and BOS components.

- Construction stage.

  This phase includes the transport of modules and BOS components to the PV plant location and the installation.

- Use stage.

  This phase includes maintenance, repair, and replacement.

- End-of-life stage.

  This phase includes deconstruction, dismantling, recycling, or disposal.

Starting from the IEA Guidelines, a framework is developed to evaluate the inclusion of each phase in the 129 contributions analyzed. The framework includes six phases: modules manufacturing, BOS manufacturing, transportation of PV components from manufacturing to installation site, installation of the PV system, use, end-of-life. Essentially, the developed framework represents a more detailed breakdown of the subdivision provided by the IEA Guidelines. Figure 15 shows the number of contributions including each of the six phases.

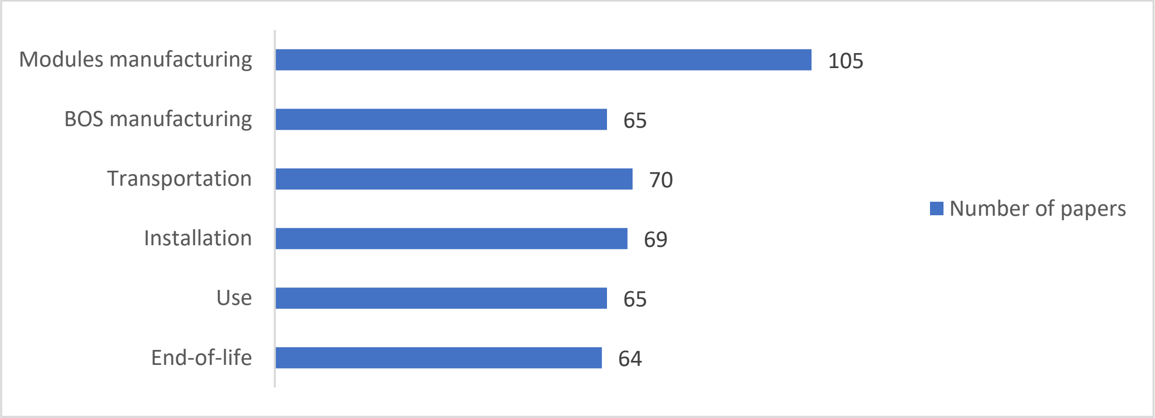

Figure 15: Inclusion of the lifecycle phases in the literature analyzed (Own production).

Firstly, modules manufacturing is the phase most often included in the contributions analyzed, confirming the great attention given to its environmental impact. This is justified by the fact that it is the phase accounting for the majority of

the environmental impact, as observed for example in Kim et al. (80).
Second, end-of-life phase is considered only 64 times: this is justified by the lack of data for such a phase, as observed for example in the review from Gerbinet et al. (47), in Rahman et al. (36) and in Nordin et al. (83). It is important to mention that 9 papers focus exclusively on the end-of-life phase, such as those from Monteiro Lunardi et al. (97) and Latunussa et al. (57). This is justified by the attention arising in the literature regarding the topic of PV waste, fundamental for the future sustainability of PV systems (98) (99). The scarcity of studies including the end-of-life phase is observed by multiple authors, including Herceg et al. (99), Maani et al. (98), and Gerbinet et al. (47).
Third, use and BOS manufacturing phases appear in 65 papers. The use phase is often not included since considered negligible, such as in Rahman et al. (36). Also, the BOS manufacturing phase is often not considered, for example since same papers are focusing only on PV modules, the core technology of a PV system, such as Muller et al. (74).
To conclude, it is observed that only 31 out of 129 papers cover all the six phases included in the framework. The scarcity of studies covering the full life cycle and including the end-of-life phase is considered a gap of the literature. Chatzisideris et al. (88) show in their review the limited number of studies covering the full life cycle and including the end-of-life stage. The gap is considered relevant for two reasons. First, the inclusion of the full life cycle is important to minimize the risk of burden-shifting across the different life cycle phases (88). Second, assessing the impact of the end-of-life phase is fundamental for the future sustainability of PV systems (98) (99).

2.2.2.5. Software

The current paragraph evaluates the type of software applied to carry out the LCA analysis. Figure 16 shows the three most frequently adopted software in the literature analyzed and their respective number of appearances.

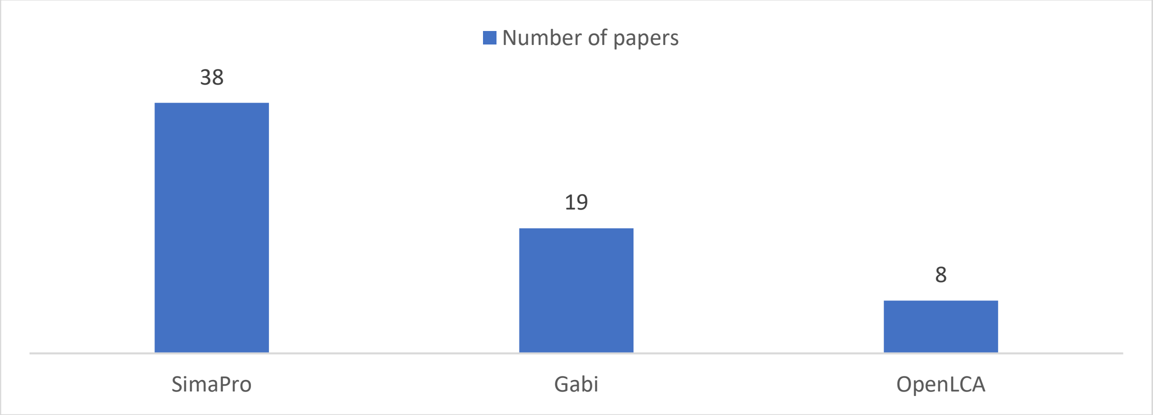

Figure 16: Most frequently adopted software in the literature analyzed (Own production).

SimaPro and Gabi are the most diffused LCA modeling software in the sample analyzed. As a matter of fact, SimaPro is considered the most diffused software in the market (100). Another option appearing 8 times is OpenLCA, an open-source software (100). Other software applied in the sample analyzed include e-balance (2 appearances), MILCA (2 appearances), and e-footprint (1 appearance). It is observed that the usage of an LCA software to carry out the analysis is the most common choice in the sample analyzed: it is applied in 76 out of 129 contributions. Furthermore, it is noticed the existence of contributions performing the analysis without using commercial LCA software, but developing instead a tailored model, that can be implemented in a spreadsheet application (101). Tailored models are considered of simpler use than LCA software, thus permitting to a wider range of users to carry out a sustainability assessment (101). It is evaluated that only 16 contributions fall within this category, thus representing a minority with respect to the 76 contributions using LCA software. An example of a contribution falling within the tailored model category is the one from Rahman et al. (36). The authors create a model to assess the environmental impact of a PV system in Bangladesh: starting from the energy requirement in the various phases of the life cycle and the grid carbon intensity, the model computes the energy requirements and the CO_2 emissions released during the life cycle of the PV system.

As mentioned above, a limited number of contributions apply a tailored model to perform the analysis. In addition, it is observed that existing tailored models present some limitations. The first limitation is related to the inclusion of the full life cycle within the boundaries of the analysis. It is observed that only 5 out of the 16 tailored models include within the boundaries of the analysis all the six phases composing the life cycle included in the framework presented in Paragraph 2.2.2.4. As a matter of fact, the inclusion of more phases of the life cycle is mentioned as an avenue for future research by authors of some models. For example, Serrano-Lujan et al. (102), authors of a model to select the best manufacturing-installation countries combination across a total of 138 countries, mention the importance of including the

BOS components in future studies given their non-negligible impact in terms of cumulative energy demand (102). The second limitation of existing tailored models is represented by the limited comparisons across PV technologies. It is evaluated that only 3 out of 16 tailored models include more than one module technology in their analysis. An example is given by the model from Serrano-Lujan et al. (102), including crystalline silicon, CdTe, and OPV modules.

2.2.2.6. Sensitivity analysis

The current paragraph investigates the inclusion in the contributions analyzed of sensitivity analyses, considered useful to evaluate the influence of selected parameters on results and facilitates comparisons among different studies (12). It is evaluated that 43 out of 129 contributions include sensitivity analyses. The most included parameter in sensitivity analyses is the irradiation, found in 14 contributions. This is explained by the fact that the irradiation has a strong impact on the energy produced by the PV system and on metrics such as the global warming potential and the EPBT. The second and the third parameters included with the highest frequency in sensitivity analyses are the system lifetime (included 13 times), and the module conversion efficiency (included 11 times). This evidence from the literature is reasonable given the strong impact of the two parameters on the energy produced by the system over its lifetime. Other parameters appearing with a lower frequency in sensitivity analyses include the performance ratio, as for example in Nordin et al. (83), the grid carbon intensity of the manufacturing country, as in Lima et al. (61), as well as the energy consumption in the modules manufacturing phase, as in Vellini et al. (103).

2.2.3. PV system hypothesis

The current subsection presents the most important assumptions regarding the PV system adopted in the sample of contributions. The assumptions examined include the location of modules and BOS components manufacturing, the installation location, the modules technology, the type of installation, and the inclusion of storage systems.

2.2.3.1. Modules manufacturing location

Figure 17 shows the five geographies most frequently considered as the modules manufacturing location in the contributions analyzed and their respective number of appearances.

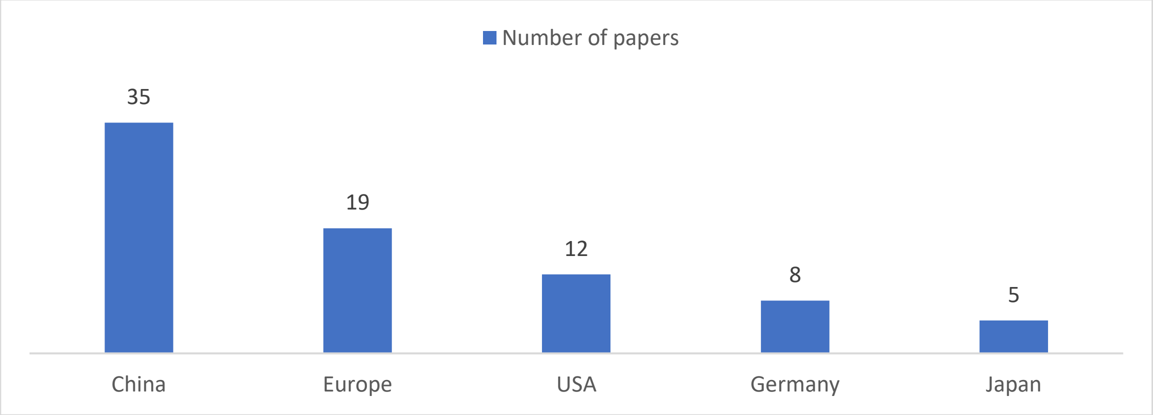

Figure 17: Most frequent modules manufacturing locations in the literature analyzed (Own production).

It is observed that China, Europe, and USA are the most selected module manufacturing locations, demonstrating the high attention given to those three geographies in the literature. This is justified by their high manufacturing output: IEA Special Report on PV Supply Chain demonstrates that they accounted for over 70% of global modules production in 2021 (32). It is observed that Italy is never considered as the manufacturing location in the contributions analyzed. This is justified by its limited modules manufacturing capacity, equal to 1.1 GW in 2021 (104). To conclude, it is mentioned that only 20 different geographies are considered as the modules manufacturing location across the 129 contributions analyzed. This can be explained by the fact that modules manufacturing supply chain is one of the most concentrated supply chains globally (32).

2.2.3.2. BOS manufacturing location

Mukisa et al. (105) mention that in most cases modules and BOS components are not imported from the same country. Thus, the locations of manufacturing of the BOS components are now evaluated. Three options are considered in this step:

1. BOS components are manufactured in the same country as PV modules.
2. BOS components are manufactured in a different country than PV modules.
3. A combination of option 1 and option 2, namely some BOS components are manufactured in the same country producing PV modules and other components in a different country.

Figure 18 provides the number of contributions included in the three abovementioned options.

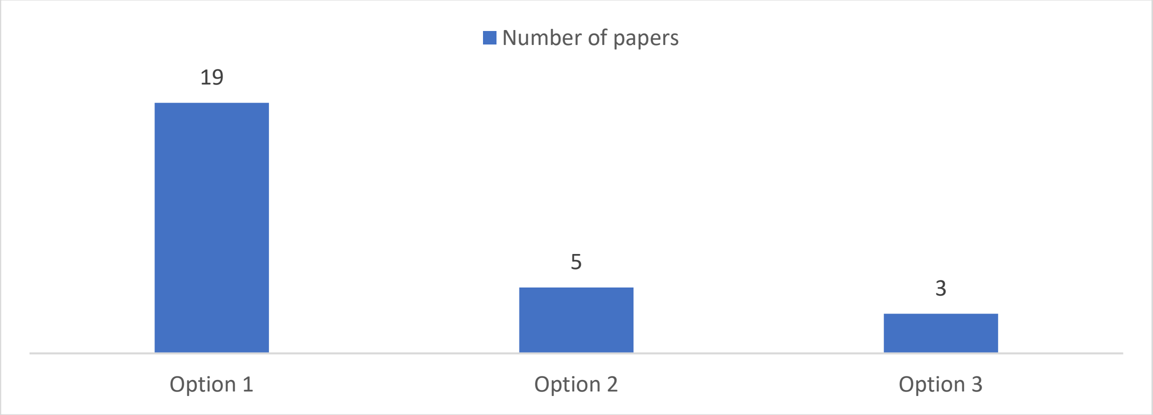

Figure 18: Location of BOS components manufacturing in the literature analyzed (Own production).

Figure 18 provides two main insights. First, it is observed that only a total of 27 appearances are counted. This is due to the fact that many scholars either do not include the BOS in their analysis, such as Pal and Kilby (106), or do not specify the country where BOS components are manufactured, such as Beylot et al. (107). Second, it is detected a limited number of contributions considering the manufacturing of BOS components to happen in a different country with respect to modules. An example is given by Eskew et al. (37), considering an installation in Thailand composed of modules manufactured in Thailand, mounting structure produced in Australia, and inverter and cabling manufactured in India. The scarcity of contributions considering different countries for the manufacturing of the various components of the PV system is considered a gap of the literature since the inclusion of multiple locations for the manufacturing of PV modules and BOS components create scenarios more representative of real market dynamics, since in most cases BOS components and PV modules are not imported from the same country (105).

Considering a country subdivision, Figure 19 provides the three geographies most frequently considered as the manufacturing location of BOS components and their respective number of appearances.

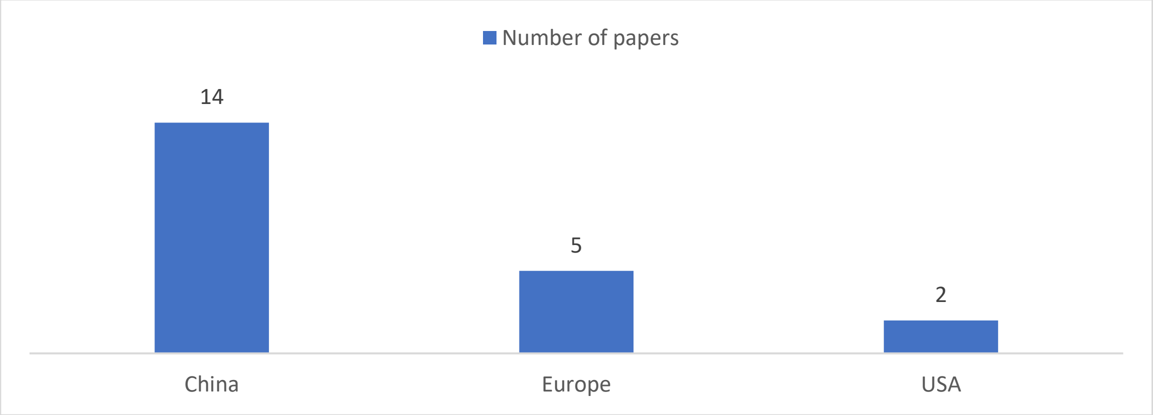

Figure 19: Most frequent BOS manufacturing locations in the literature analyzed (Own production).

It is observed that China is the country most often considered as the manufacturing location of the BOS components. This can be justified by its relevant market share in the production of important BOS components: for example, the IEA estimates that China accounted for 67% of worldwide inverter production in 2020 (15).

2.2.3.3. Installation location

Figure 20 shows the five geographies most frequently considered as the installation location in the sample analyzed and their respective number of appearances.

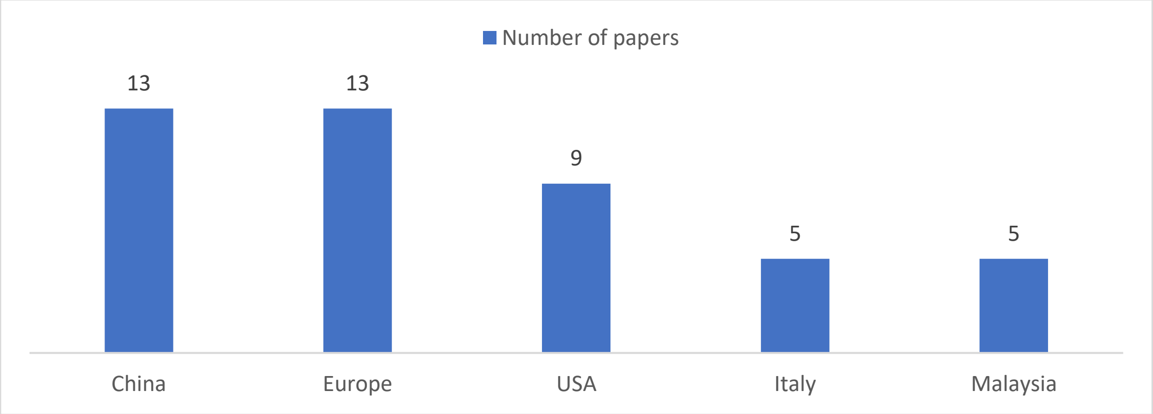

Figure 20: Most frequent installation locations in the literature analyzed (Own production).

It is observed that China, Europe, and USA top the list. This can be justified by the high installed capacity in those geographies: BP Statistical Review of World Energy shows that they represent 70% of global cumulative PV installed capacity as of the end of 2021 (108). It is observed that a limited number of contributions consider as the place of installation Africa (3 papers) or Latin America (5 papers). This can be explained by the fact that those areas account for less than 4% of the global cumulative PV installed capacity (108). The limited coverage of the African continent is mentioned by Ito et al. (109), stating in a paper from 2016 that no LCA analysis exists to the knowledge of the authors for PV systems located in Africa. To conclude, it is observed that the distribution of the installation locations is sparser with respect to the locations of modules manufacturing: 33 different locations are considered as the installation, while it was observed in Paragraph 2.2.3.1 that only 20 different geographies are considered as the modules manufacturing location.

2.2.3.4. Modules generation and technology

The current paragraph analyzes the inclusion of the three generations of PV technologies in the literature. Figure 21 provides the frequencies observed in the sample analyzed. To better understand the classification, a paper is classified as 'First' if it includes only the first generation of PV technologies, while it is classified as 'First + Second' if it includes both the first and the second generations of PV technologies.

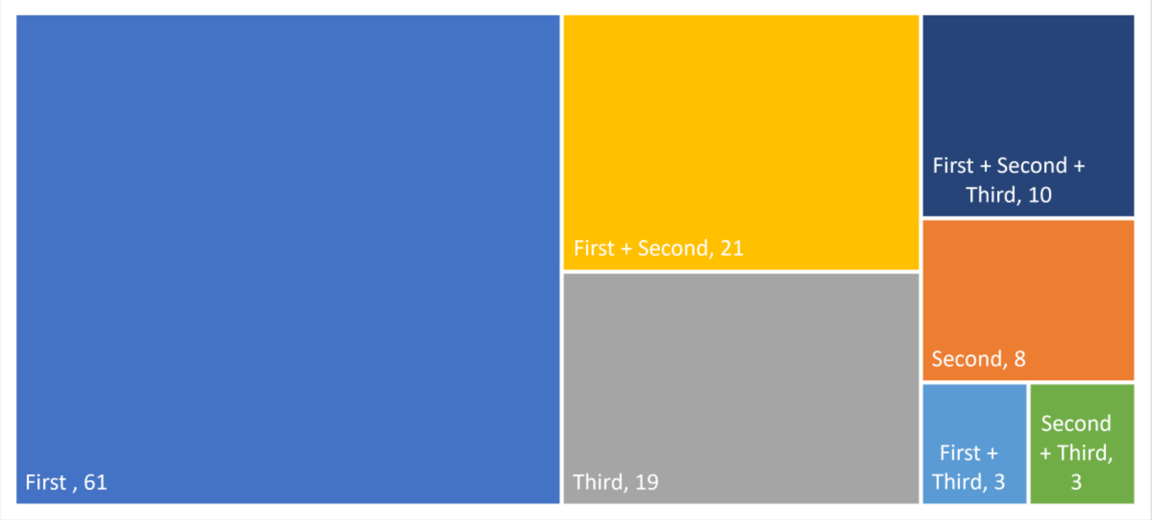

Figure 21: Number of appearances of PV generations in the literature analyzed (Own production).

The frequencies observed in the literature analyzed demonstrate the higher attention provided to first generation technologies. This can be justified by the fact that they accounted for over 85% of modules production every year since 2010 (17). It is also observed that there are more studies focusing exclusively on third generation technologies than on second generation ones. This can be explained by the high research effort towards third generation technologies arising in recent years (14). Finally, it is observed that only 10 contributions include all the three generations of PV technologies within the analysis. Those 10 contributions include both reviews, such as the one from Ludin et al. (78), and journal articles, such as the one from Serrano-Lujan et al. (102).

It is now examined the inclusion of the different PV technologies in the literature. Figure 22 provides the frequencies observed in the sample analyzed. The technologies considered are the most representative for the three different generations, as presented in Section 1.2: monocrystalline, multicrystalline, CdTe, CI(G)S, a-Si, OPV, perovskite, DSSC.

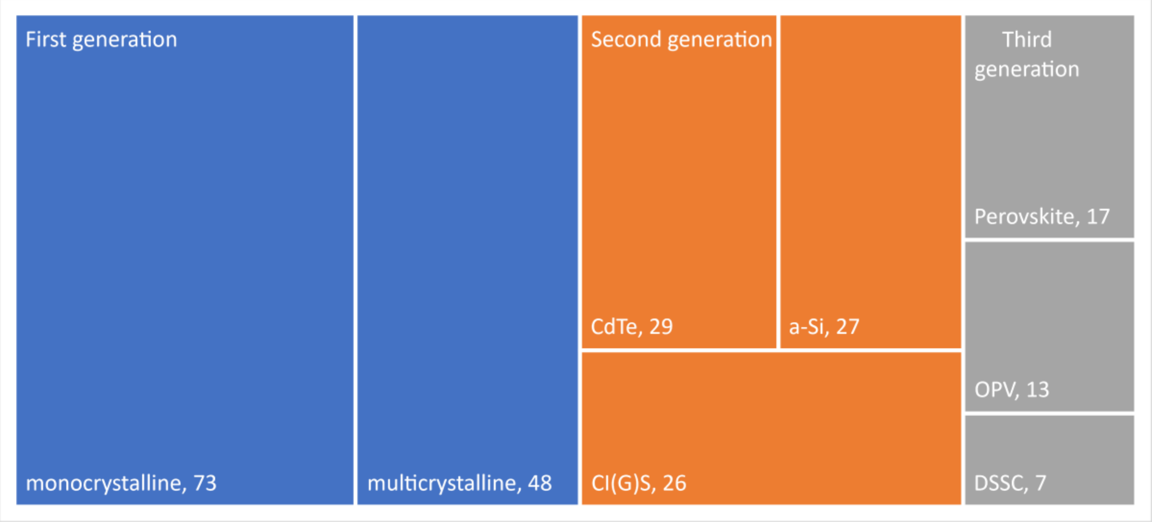

Figure 22: Number of appearances of the different PV technologies in the literature analyzed (Own production).

It is observed that multicrystalline and monocrystalline are the most frequently assessed technologies, appearing in 73 and 48 papers respectively. As a matter of fact, they accounted for over 85% of modules production every year since 2010 (17). Considering second generation technologies, the most analyzed is the CdTe option. This can be explained by its historically higher market share within the second generation of PV technologies (17). Third generation PV technologies appear less frequently in the literature: this can be justified by their negligible market share (16). Whitin the third generation, the most assessed technologies are the perovskite and the organic options. As a matter of fact, IEA Photovoltaic Trends Report mentions that organic PV has created a large research interest in recent years (15).

It is observed that the inclusion in the same paper of multiple technologies is limited. Only 11 out of 129 papers include a comparison of the five most diffused PV technologies (monocrystalline, multicrystalline, CdTe, CI(G)S, a-Si) (17). Example of contributions included in this category are those from Liu and van den Bergh (110) and Laleman et al. (60). The former (110) analyze the differences in environmental impact depending on the technology considered, including in the analysis monocrystalline, multicrystalline, CdTe, CIS, and a-Si technologies. The latter (60) perform an LCA on rooftop installations including multiple modules technologies, namely monocrystalline, multicrystalline, a-Si, ribbon silicon, CIS, and CdTe. Similarly, it is observed that only 10 contributions in the literature include a comparison of the impact of technologies belonging to all generations. Examples include the paper from Serrano-Lujan et al. (102), comparing crystalline silicon, CdTe, and OPV technologies on metrics such as the EPBT and the energy return factor, as well as Tsang et al. (96), including organic, multicrystalline, and amorphous silicon technologies and comparing them on metrics such as the cumulative energy demand and the EPBT.

The limited comparison across technologies in the literature is observed by Rashedi and Khanam (73), mentioning in their paper from 2020 the absence of contributions comparing the four most common PV technologies by ReCiPe methodology. The scarcity of contributions proposing a comparison across the most adopted PV technologies, as well as a comparison including all the generations of technologies, is considered a gap of the literature. As a matter of fact, the comparisons of PV technologies available on the market can provide useful industrial and policy implications. Furthermore, the importance of comparing different technologies in the same LCA study is due to the fact that the results of an LCA study are intrinsically dependent on the assumptions taken, so that comparing the results from different studies is not equivalent to the comparison of different technologies within the same one.

2.2.3.5. Installation configuration

It is now analyzed the inclusion of rooftop or ground-mounted PV systems in the literature. The frequencies observed in the sample analyzed are provided in Figure 23.

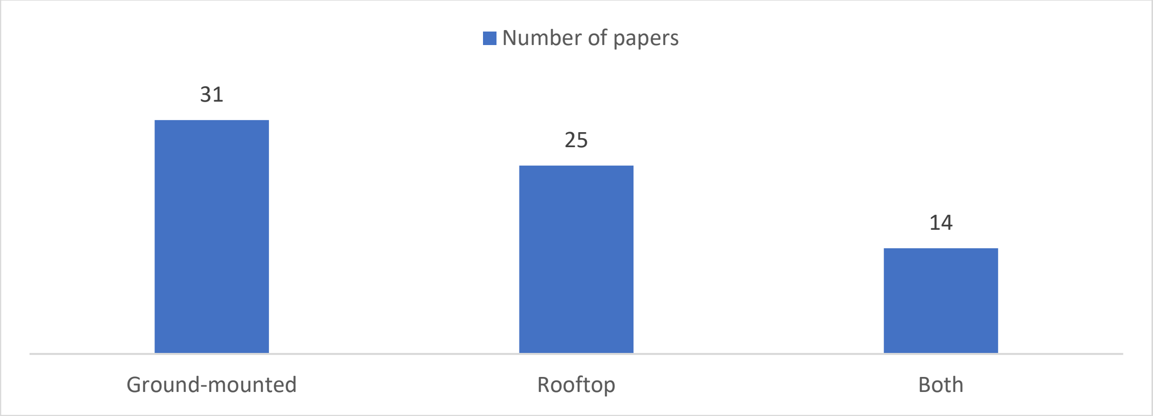

Figure 23: Installation configurations encountered in the literature analyzed (Own production).

The slightly higher number of contributions considering ground-mounted systems can be explained by the higher cumulative installed capacity of utility-scale ground-mounted systems versus rooftop installations (19). It is observed that only

70 contributions are included in Figure 23: for the remaining papers the analysis of a rooftop or ground-mounted system is either not specified or not applicable, for example since the analysis is focusing only on cell or module production, thus excluding the installation and use phases. Examples are given by Chen et al. (111), covering monocrystalline cell production, and by Carneiro et al. (112), analyzing the manufacturing of perovskite solar cells.

2.2.3.6. Emerging PV applications

It is here analyzed the inclusion of emerging PV applications, such as building integrated photovoltaic (BIPV), building applied photovoltaic (BAPV), floating PV, and agrivoltaic systems (15).

BIPV refers to the substitution of conventional building materials by some that contains PV modules, while BAPV refers to the application of PV on existing buildings (15). It is observed that 15 papers include BIPV, and 1 paper includes BAPV in their analyses. BIPV is defined as a niche market that can be considered as summing up to 1 GW of cumulative installed capacity (15). Given such a small market, 15 contributions in the literature may appear a lot. The high number of contributions encountered in the sample can be explained by the numerous types of systems falling under the definition of BIPV. This includes modules replacing the roof (113), façade-integrated PV (114), and semi-transparent PV windows (79) (115). The sample of contributions also includes a review focusing exclusively on BIPV (116).

Only 1 paper (117) analyzes a floating PV system. This is justified by the fact that floating PV is a relatively recent application with a cumulative installed capacity of only 6 MW in 2013 and expanding to 3 GW in 2021 (15).

An agrivoltaic system is defined by the Fraunhofer Institute as an application simultaneously using land to produce crops and generate PV electricity (21). Only 5 papers include an agrivoltaic system in their analysis. For example, Agostini et al. (118) perform an LCA on an agrivoltaic system located in Italy, while Choi et al. (119) analyze the combined use of land for solar PV and agriculture in Indonesia. The scarce coverage of agrivoltaic systems in the literature is justified by the fact that they are a recent technology, accounting for only 5 MW of installed capacity in 2012 and expanding to 14 GW in 2021 (120).

2.2.3.7. Storage system

The variability of PV generation and the mismatch between energy supply and demand call for the need of storage systems. Different technologies exist to store energy from PV technologies. At very large scale, pumped hydro energy storage is considered the only option for an economic storage of energy (16). The other option consists in electrochemical energy storage: for PV systems, Li-ion technology represents currently 90% of the market (16). The first observation from the literature analyzed is that the storage system that can be associated to the PV plant is often not analyzed: in 119 out of 129 contributions it is either not cited or expressly not included. Fthenakis and Leccisi (23) comment that the usage of battery-based storage is expected not to significantly affect the better environmental performance, for example in terms of carbon footprint, of PV versus conventional thermal power generation. As a matter of fact, Raugei et al. (82) demonstrate that adding a lithium-ion battery to a utility-scale PV system, leads to an increase in EPBT and in global warming potential by 7% to 30%, depending on the irradiation and storage scenarios considered.

2.2.4. PV technical parameters

2.2.4.1. Module efficiency

The module efficiency is an important parameter to define the energy produced by a PV system. Figure 24 shows the distribution of module efficiencies encountered in the sample analyzed for the main PV technologies. It is observed that many reviews, such as the one from Ludin et al. (78), provide in a tabular format the values of the efficiencies encountered in the literature. Those values from reviews are not included in Figure 24 but are considered to check the consistency of the ranges obtained. This is done for two reasons. First, some reviews include values from contributions dating back to the early 2000s, while in the literature review have been excluded papers published before 2010. Second, some reviews do not clearly indicate whether the reported efficiency refer to cells or to modules, as the one from Muteri et al. (12), while in Figure 24 only module efficiencies are reported.

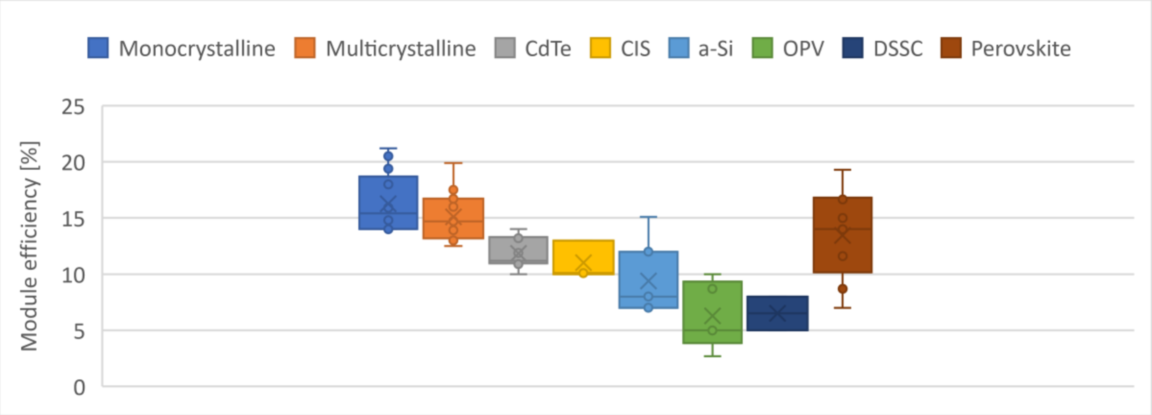

Figure 24: Module efficiencies encountered in the literature analyzed (Own production).

It is observed that first generation technologies show higher average module efficiencies than second and third generation technologies. Among the first generation technologies, the monocrystalline option features the highest average efficiency. Within second generation technologies, CdTe presents a slightly higher average efficiency than CIS or a-Si technologies. Data from papers published after 2010 reported in the review from Ludin et al. (78) confirm this finding. OPV and DSSC technologies show lower average efficiencies than first- and second-generation ones. Perovskite technology shows the highest average efficiency within third generation technologies: as a matter of fact, Correa Guerrero et al. (121) mention the high research interest they are creating due to their conversion efficiency.

It is important to mention the considerable variance observed within the same technology. For example, considering the perovskite technology, efficiency ranges from a minimum of 7% in Zahedi et al. (13), to a maximum of 19.3% in Leccisi and Fthenakis (122). The remarkable variance characterizing the efficiency of perovskite modules is observed also in the values reported in the review from Ludin et al. (78).

2.2.4.2. Irradiation

The irradiation is a fundamental parameter to determine the electricity produced by a PV system. The most applied unit of measurement for the irradiation is the kWh/(m²*year). The values of the irradiation encountered in the literature range between 573 and 2500 kWh/(m²*year). The minimum is mentioned in the review from Peng et al. (85), since applied in a paper studying an installation in a low solar irradiation region (123). The maximum is observed in the paper from Reich et al. (124) for an installation located in the Sahara desert. Furthermore, it is observed that three papers provide the same segmentation for low, mid, and high irradiation regions. Those are the papers from Raugei et al. (82), Leccisi et al. (125) and Fthenakis and Leccisi (23). It is observed that two scholars, namely Leccisi and Fthenakis, are included as authors in all the three papers. Table 4 provides the segmentation proposed in the three papers.

Range	Irradiation [kWh/(m²*year)]	Examples of region
Low	1000	UK
Middle	1700	Southern Europe, New York
High	2300	Arizona

Table 4: Example of a segmentation of solar irradiation (82) (125) (23).

Given that irradiation has a significant influence on the energy produced by the PV system, some papers perform a sensitivity analysis on its value. In Paragraph 2.2.2.6

it has been demonstrated that irradiation is the parameter most often subject to sensitivity analyses in the literature analyzed.

2.2.4.3. Lifetime

Lifetime is an important parameter to define the energy produced by a PV system. Figure 25 provides the distribution of the values encountered in the sample analyzed for the lifetime of first- and second-generation modules.

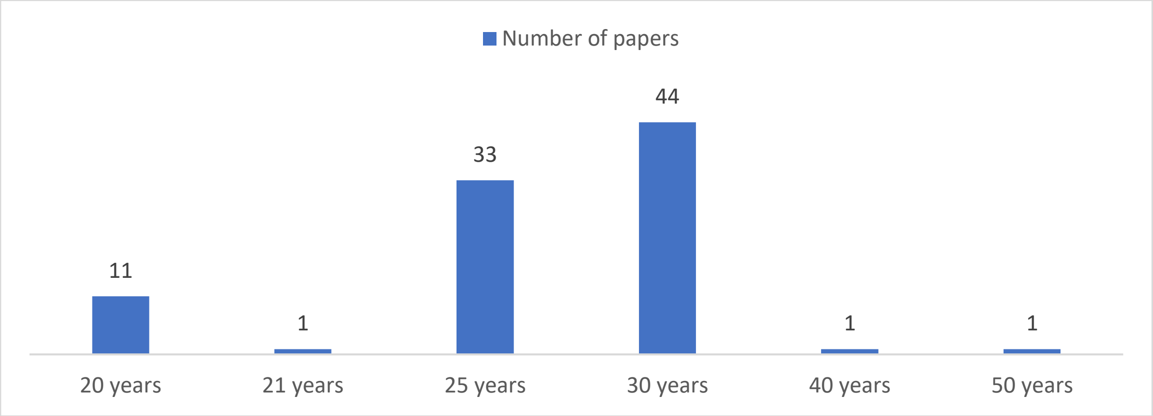

Figure 25: Lifetime for modules of first and second generation encountered in the literature analyzed (Own production).

Figure 25 shows that the most common values of the lifetime for first and second generations technologies are equal to 25 and 30 years. The outliers of 40 and 50 years are mentioned in Stylos and Koroneos (126), since the authors are considering a prospective scenario with an increased lifetime due to more reliable PV systems. The results obtained in Figure 25 are confirmed by the literature: Laleman et al. (60) mention that most authors consider a lifetime ranging from 25 to 30 years, while the review from Ludin et al. (78) shows that the lifetime of PV systems based on first- and second-generation technologies ranges between 20 and 30 years. Emerging technologies are characterized by a shorter lifetime compared to first and second generations ones. Considering OPV modules, Leon and Ishihara (127) assume a lifetime of 10 years, 15 years are assumed by Garcia-Valverde et al. (128), and in the review from Gressler et al. (69) it is indicated a lifetime ranging from 1.5 to 20 years. Moving to perovskite technology, a lifetime of 1 years is considered in Espinosa et al. (129), while Tian et al. (130) assume the value of 5 years, and the range from 1 to 20 years is indicated in the review from Gressler et al. (69). Considering the lifetime of DSSC modules, a great variance is observed in the literature: Blaszczyk et al. (65) assume the value of 1 year, while 20 years are assumed by Parisi et al. (131). It is important to remember that the limited lifetime of third generation technologies is a brake to their commercialization (16).

In addition to the lifetime of modules, it is often defined the lifetime of selected BOS components. The BOS component whose lifetime is cited with the highest frequency in the sample analyzed is the inverter. The most frequently cited lifetimes for the inverters are 15 years (cited in 8 contributions) and 10 years (cited in 7 contributions). The results obtained are confirmed by selected scholars: Hou et al. (132) and Yu et al. (25) mention that the typical lifetime of inverters is 10 to 15 years. Since the lifetime of inverters is lower than those of first and second generations modules, replacements are needed (132). Another BOS component whose lifetime is mentioned more rarely in the sample analyzed is the battery associated to the PV system. Uctug and Azapagic (66) as well as Stylos and Koroneos (126) mention a lifetime of 10 years for the battery, while Nicholls et al. (133) indicate a value equal to 15 years. The lifetime of other BOS components, such as the mounting structure and the cabling, is indicated more rarely in the sample analyzed. Herceg et al. (99) consider a lifetime of 30 years for the mounting structure and the cabling. The values indicated suggest that those components do not need a replacement over the typical lifetime of PV systems.

2.2.5. Modeling approaches

The current subsection presents the modeling approaches adopted in the contributions analyzed for each of the phases composing the life cycle. In accordance with the framework proposed in Paragraph 2.2.2.4, the six following phases are considered: modules manufacturing, BOS manufacturing, transportation, installation, use, end-of-life. Furthermore, the approaches adopted in the literature to model the electricity produced by the PV system are presented. For each phase, the literature is analyzed to find:

- The definitions adopted.
- The modeling approaches applied.
- The impact of the phase in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions with respect to the full life cycle.

The following paragraph covers the approaches adopted to model the electricity produced by the PV system.

2.2.5.1. Electricity production

The electricity produced over the lifetime of a PV system can show a wide variability, for example due to the different values of solar irradiation at different locations (124). The simplest approach found in the literature to model the electricity generated by a PV system consists in the multiplication of the irradiation rate, the active area, and the conversion efficiency. This approach is observed for example in Wu et al. (86) and Soares et al. (134). Other authors include an additional factor in the formula: the performance ratio. This methodology is observed for example in Mehedi et al. (135), in Clemons et al. (117), and in Ludin et al. (38). The performance ratio is defined by the International Electrotechnical Commission as the ratio between the system's final yield and its ideal yield (27). Adding a further level of detail, some authors also include the degradation of efficiency in the computation of the energy yield. Examples of contributions including the degradation rate in the computation of the electricity yield are Kim et al. (81), Antonanzas et al. (75), and Muller et al. (74). The degradation rate indicates the reduction of efficiency of PV modules over time (27). As an example, it is shown the formula applied by Muller et al. (74) to compute the electricity output over the lifetime of the PV system:

$$E = \sum_{y=1}^{T} (1 - DR)^{y} * I * A * \eta * PR$$

Where:

- y indicates the year.
- T is the lifetime of the PV system in years.
- DR is the mean annual degradation rate [%/year].
- I represents the irradiation [kWh/(m^{2}*year)].
- A is the area of PV modules [m^{2}].
- η is the module conversion efficiency [%].
- PR is the performance ratio [%].

In addition to the methodologies described above, it is observed that some authors employ specific software to compute the electricity output of the PV system. The literature analysis demonstrates that different software exists to simulate the electricity output of PV systems. For example, SAM is a software developed by the NREL permitting the selection of appropriate meteorological and technical data for the installation (136). It is applied by Ritzen et al. (136), by Mukisa et al. (105), as well as by Martinopoulos (137). Other example of software employed in the literature analyzed include PVSyst, used by Bayod-Rujula et al. (87), HOMER, employed by Eskew et al. (37), and TRNSYS, chosen by Wang et al. (138). To conclude, it is mentioned by Anctil et al. (95) the usage of RETScreen, a software developed by the government of Canada allowing to assess renewable energy projects (139).

2.2.5.2. Modules manufacturing

The most common definition encountered in the literature considers the modules manufacturing phase as starting with the extraction of raw materials and ending with the production of finished modules. A similar definition can be found for example in Jia et al. (140), in Pal and Kilby (106), and in Mehedi et al. (135). To have a better idea of the manufacturing process of PV modules, a brief presentation is here provided for first generation technologies (80). First, silica from quartz sand is transformed into metallurgical grade silicon using an arc furnace. Then, it is purified into poly-silicon thanks to the Siemens process. The subsequent crystallization is the main difference between monocrystalline and multicrystalline ingots: the former are crystallized by the energy intensive Czochralski process, requiring temperatures up to 1500°C, the latter are melted and casted into blocks of multicrystalline silicon without the need of such an high temperature. The ingots are then sliced into wafers. Wafers are processed into cells by procedures including etching, texturing, and formation of the emitter layer. Cells are laminated with glass and ethylene vinyl acetate (EVA), and then heated for encapsulation by melting the EVA. Aluminum-based frames and cables are then used to assemble the PV modules (80).

Different modeling approaches for the modules manufacturing phase are encountered in the literature. Starting from the authors developing a tailored model instead of using an LCA software, it is observed that Hou et al. (132) compute the energy consumption during modules manufacturing by multiplying a factor in kWh/W by the capacity of the system. Mukisa et al. (105) adopt a similar approach, considering in addition the energy efficiency of the country of manufacturing. Other authors estimate the energy consumption during the process of modules manufacturing starting from a specific factor related to the surface. For example, Rahman et al. (36) multiply the primary energy requirement in kWh/m^2 by the area of modules. A similar approach is found in Serrano-Lujan et al. (102), that compute the energy needed to manufacture PV modules according to the following formula:

$$E_{emb} = S * E_m$$

Where:

- E_{emb} is the energy consumption during modules manufacturing in kWh.
- S is the surface of PV modules in m^2.
- E_m is the required electricity to manufacture the modules in kWh/m^2.

The impact in terms of $CO_{2\text{-eq}}$ emissions of the modules manufacturing phase is evaluated in multiple contributions starting from the energy consumption of the manufacturing process and considering the grid carbon intensity of the country of manufacturing. For example, Hou et al. (132) compute the emissions from the modules manufacturing process according to the following formula:

$$GHG = \frac{GHG_{grid} * E}{Q}$$

Where:

- *GHG* indicates the emissions generated during the modules manufacturing process in gCO_{2-eq}/kWh.
- GHG_{grid} is the carbon intensity of the grid supplying the manufacturing process, in gCO_{2-eq}/kWh.
- *E* is the energy consumption of the modules manufacturing process in kWh/W.
- *Q* is the energy output per watt of the system in kWh/W.

A similar methodology is observed in Mukisa et al. (105), where the scholars also include the energy efficiency of the industrial sector of the country of manufacturing, according to the following formula:

$$CO_2 = E_{Manufacturing} * (1 - \alpha) * CO_{2\,grid}$$

Where:

- CO_2 indicates the emissions generated during the modules manufacturing process in gCO_2/W.
- $E_{Manufacturing}$ represents the energy consumed during the modules manufacturing process in kWh/W.
- α represents the energy efficiency of the industrial sector of the manufacturing country.
- $CO_{2\,grid}$ is the grid carbon intensity in gCO_2/kWh of the manufacturing country.

As demonstrated in Paragraph 2.2.2.5, most contributions in the literature analyzed employ specific LCA software, such as SimaPro or GABI, to perform the LCA analysis. In those cases, the approach to carry out the analysis do not employ a tailored model as for example the one from Mukisa et al. (105) mentioned above. Instead, the analysis starts with the definition of the inventory of materials and energy needed to manufacture modules, as it is observed for example in Fu et al. (141). The inventory represents the input for the software, that automatically computes the environmental impact (142). The environmental impact categories computed depend on the chosen LCIA methodology: in Paragraph 2.2.2.3 it has been demonstrated that the most applied in the literature analyzed is ReCiPe. An example of a contribution compiling the inventory of energy and materials needed in the modules manufacturing process and using an LCA software to carry out the analysis is given by Huang et al. (70), using GABI to compute the midpoint impact categories of ReCiPe. Similarly, Nordin et al. (83) adopt SimaPro and evaluate the impact of the modules manufacturing in terms of the impact categories of ReCiPe. Finally, it is observed that both Fu et al. (141) and Resalati et al. (68) use GABI and assess the impact of cells and modules manufacturing according to CML impact categories.

Following the structure presented at the beginning of Subsection 2.2.5, it is now analyzed the impact in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions of the modules manufacturing phase in percentage with respect to the full life cycle. Figure 26 shows the distribution of the values encountered in the 129 contributions composing the sample analyzed. The details of the plotted values and the respective sources are provided in Appendix A.2.

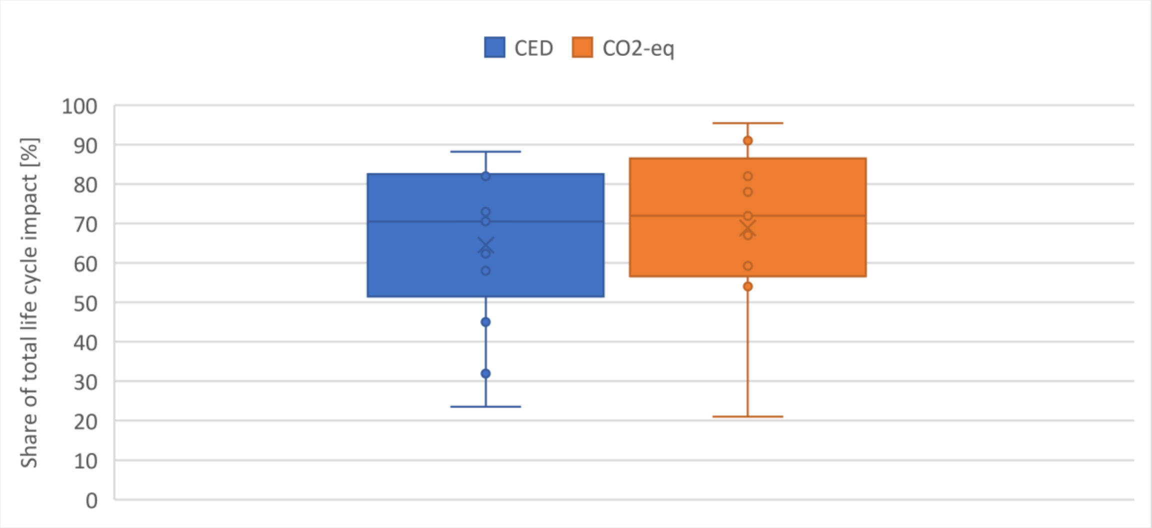

Figure 26: CED and $CO_{2\text{-eq}}$ emissions from the modules manufacturing phase in percentage with respect to the impact of the full life cycle (Own production).

Considering the impact of the modules manufacturing phase in terms of cumulative energy demand, Figure 26 shows the large variability encountered in the literature, ranging from a minimum of 23.49% to a maximum of 88.19% of the total CED over the life cycle. The minimum is computed from the results shown by Li et al. (79) and can be justified by the fact that authors are including the battery within the boundaries of the system, so that modules manufacturing contributes with a lower percentage to the total primary energy demand. The maximum is mentioned by Jia et al. (143) in a paper analyzing multicrystalline silicon technology in China. The high value can be explained by the fact that authors are excluding BOS components from the boundaries of the analysis, so that the relative impact of the modules manufacturing phase with respect to the full life cycle is higher.

$CO_{2\text{-eq}}$ emissions from the modules manufacturing phase show a large variability, moving from a minimum of 20.99% to a maximum of 95.31% of total life cycle emissions. The minimum is computed from the results indicated in Li et al. (79) and can be justified by the inclusion of the battery within the boundaries of the system, so that modules manufacturing contributes with a lower percentage to the total emissions over the life cycle. The maximum is calculated from the results indicated in Muller et al. (74) and can be justified by the exclusion of BOS components from the boundaries of the analysis, so that modules manufacturing contributes with a higher share to total emissions.

2.2.5.3. BOS manufacturing

A common definition encountered in the literature considers BOS components as all the parts of a PV system different than PV modules (25) (144). As such, the definition includes the mounting structures, inverters, cabling, and interconnection equipment (132). Large scale ground-mounted installations require additional components and facilities, such as grid connection equipment and offices (145). For stand-alone systems, batteries are usually included in the BOS, as for example in Rahman et al. (36) and in Mustafa et al. (146). Furthermore, it is observed that different contributions include different activities within the boundaries of the BOS phase. For example, Antonanzas et al. (75) define the BOS phase as comprehensive of site conditioning, mounting structure manufacturing, electrical installation manufacturing, PV panels transportation, and installation. On the other hand, Fthenakis and Leccisi (23) include in the BOS phase not only mechanical and electrical components manufacturing but also operation and maintenance activities.

Different modeling approaches to estimate the impact of the BOS manufacturing phase are encountered in the literature analyzed. Starting from the authors developing a tailored model instead of using an LCA software, it is observed that the approach adopted by Hou et al. (132) consists in multiplying the capacity of the PV system by the specific factor of 0.255 kWh/W, representative of the energy consumed in the process of BOS components manufacturing, system integration and construction. Similarly, Rahman et al. (36) computes the primary energy requirement of inverter manufacturing by multiplying the factor of 0.277 kWh/W by the capacity of the inverter analyzed, while the structural components such as the steel structure and concrete are modeled starting from the specific quantity needed in kg/W and the energy requirements in kWh/kg. Wu et al. (86) compute the primary energy requirement to manufacture BOS components starting from a factor in MJ/kW for the inverter and a factor in MJ/m^2 for the remaining BOS components, that are subsequently multiplied by the total size of the system. The impact in terms of $CO_{2\text{-eq}}$ emissions of the BOS manufacturing phase is evaluated in multiple contributions starting from the energy consumption of the manufacturing process and considering the grid carbon intensity of the country of manufacturing. For example, Hou et al. (132) compute the $CO_{2\text{-eq}}$ emissions released in the process of

BOS components manufacturing and system integration according to the following formula:

$$GHG = \frac{GHG_{grid} * E}{Q}$$

Where:

- GHG indicates the emissions generated during the process of BOS components manufacturing and system integration in $gCO_{2\text{-eq}}$/kWh.
- GHG_{grid} is the carbon intensity of the grid supplying the process, in $gCO_{2\text{-eq}}$/kWh.
- E is the energy consumption of the process of BOS components manufacturing and system integration in kWh/W.
- Q is the energy output per watt of the system in kWh/W.

A similar approach is found in Nicholls et al. (133), estimating the $CO_{2\text{-eq}}$ emissions due to BOS components manufacturing by multiplying the embodied energy [GJ] of BOS components by a factor of 60 $kgCO_{2\text{-eq}}$/GJ representative of the grid carbon intensity of the manufacturing country.
As demonstrated in Paragraph 2.2.2.5, most contributions in the literature analyzed employ specific LCA software, such as SimaPro or GABI, to carry out the analysis. In those cases, the approach to complete the LCA do not employ a tailored model, as for example the one from Hou et al. (132) mentioned above. Instead, the analysis starts with the definition of the inventory of materials and energy consumed in the BOS manufacturing phase. The inventory represents the input for the software, that automatically computes the environmental impact (142). The environmental impact categories computed depend on the selected LCIA methodology: in Paragraph 2.2.2.3 it has been demonstrated that the most applied in the literature analyzed is ReCiPe. For example, Rashedi and Khanam (73) and Mustafa et al. (146) compile the inventory of materials and energy needed to manufacture BOS components, and SimaPro is the software used in the two contributions to compute the impact according to ReCiPe indicators (73) (146). Other examples of authors compiling the inventory of energy and materials for BOS components as an input for the software include Kim et al. (80) and de Wild-Scholten (147). In both contributions the software employed is SimaPro and the indicators computed include the global warming potential and the EPBT.
Lastly, it is mentioned that an important factor to consider when modeling the BOS components is the dimensioning of the inverter associated to PV modules. The metric considered to size the inverter is the inverter loading ratio, corresponding to the ratio of the PV system capacity by the inverter capacity (148). Some authors consider an inverter loading ratio different than 1. For example, Raugei et al. (82)

assume an inverter loading ratio of 1.3, so that a 77 MW inverter is associated to a 100 MW PV plant, while Rahman et al. (36) and de Wild-Scholten (147) assume a loading ratio of 1.1 and 1.16, respectively. Other authors set an inverter loading ratio equal to 1: the size of the inverter in watt and the peak power output of the PV system correspond (133). Examples of authors applying this assumption include Beylot et al. (107), Koulompis et al. (149), Uctug and Azapagic (66), and Nicholls et al. (133).

The values of the impact of the BOS manufacturing phase encountered in the 129 contributions analyzed in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions as a percentage with respect to the impact of the full life cycle are reported in Figure 27. The details of the plotted values and the respective sources are provided in Appendix A.2.

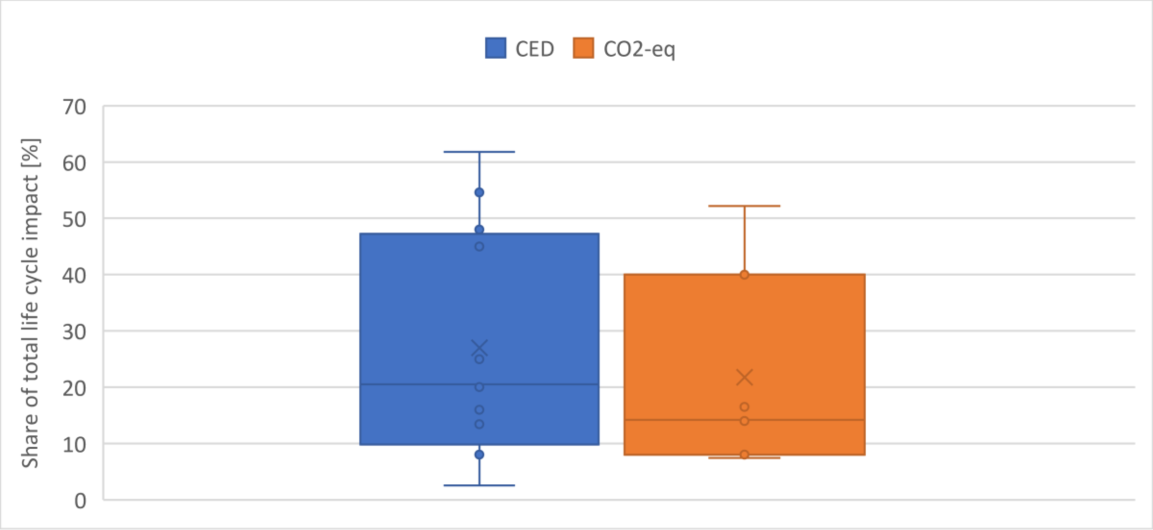

Figure 27: CED and $CO_{2\text{-eq}}$ emissions from the BOS manufacturing phase in percentage with respect to the impact over the full life cycle (Own production).

Starting from the impact of the BOS manufacturing phase in terms of cumulative energy demand, Figure 27 shows the great variability in the values encountered in the literature analyzed, ranging from 2.56% to 61.79% of the total CED over the life cycle. The minimum is computed from Sumper et al. (150) analyzing a rooftop installation in Spain, while the maximum is calculated from the results indicated in Rahman et al. (36). The higher value encountered in the latter can be justified by the inclusion of the battery within the BOS.

A similar variability is encountered for the $CO_{2\text{-eq}}$ emissions from BOS manufacturing, ranging from 7.40% to 52.20% of the total emissions over the life cycle of the PV system. The minimum is gathered from the results indicated in Mustafa et al. (146), considering the manufacturing of BOS components for a BIPV installation in Malaysia. The maximum is computed from the results shown by

Kim et al. (81), where the authors are performing an LCA on a ground-mounted system adopting CdTe modules and installed in Korea.

2.2.5.4. Transportation

The transportation phase is often defined in the literature as the delivery of PV modules and BOS components from the location of manufacturing to the installation one. Examples of authors applying a similar definition include Santoyo-Castelazo et al. (90), Ito et al. (151), Eskew et al. (37), and Bayod-Rujula et al. (87). The literature analysis suggests that the most common transport mode employed to deliver PV modules is represented by a combination of ships for water transportation and trucks for land transportation. This approach is observed for example in Mukisa et al. (105), in Stylos and Koroneos (126), in Bayod-Rujula et al. (87), and in Ito et al. (151). A similar approach combining trucks for land transportation and ships for water transportation is adopted to transport BOS components (109). Given the fact that PV modules and BOS components can be imported from different locations (105), different distances must be considered. An approach considering different manufacturing locations for modules and BOS components can be found for example in Rahman et al. (36), in Eskew et al. (37), and in Stylos and Koroneos (126).

It is discovered that the most common modeling approach to compute the impact of the transportation phase considers the distance covered, the transport mode employed, and the weight of materials transported. Starting from the authors developing a tailored model instead of using an LCA software, it is observed that in Wu et al. (86) the energy requirements for the transportation phase are obtained by the product of the specific energy requirements of the transportation process [MJ/(ton*km)], the distance covered, and the weight of modules transported. In line with the approach just mentioned, Mukisa et al. (105) compute the impact of the transportation phase in terms of energy consumption according to the following formula:

$$E = E_{sea} * M * D_{sea} + \frac{E_{road} * D_{road}}{W}$$

Where:

- E_{sea} indicates the specific energy consumption of sea freight transportation in kWh/(kg*km).
- M is the mass per watt of the modules in kg/W.
- D_{sea} and D_{road} are the distances covered per mode of transport in km.
- E_{road} is the specific energy consumption for road transportation in kWh/km.
- W is the wattage of the modules transported.

The impact of the transportation phase in terms of GHG emission is obtained by Mukisa et al. (105) with the following formula:

$$GHG = GHG_{sea} * D_{sea} * M + GHG_{road} * D_{road} * M$$

Where:

- GHG_{sea} and GHG_{road} are the specific emissions of the sea freight and road transportation in $gCO_{2\text{-}eq}/(kg*km)$.
- D_{sea} and D_{road} are the distances covered per mode of transport in km.
- M is the mass per watt of the modules in kg/W.

To conclude, it is mentioned a different approach encountered in Rahman et al. (36), modeling the transportation phase by considering the distance covered, the speed of the ship, the load factor and the lower heating value of the fuel used.
As demonstrated in Paragraph 2.2.2.5, most contributions in the literature analyzed employ specific LCA software, such as SimaPro or GABI, to complete the analysis. In those cases, the approach to carry out the computations do not employ a tailored model, as for example the one from Mukisa et al. (105) mentioned above. The analysis starts with the definition of the inventory of materials to be transported and the distance to be covered. The inventory represents the input for the software, that automatically computes the environmental impact (142). The environmental impact categories computed depend on the chosen LCIA methodology: in Paragraph 2.2.2.3 it has been demonstrated that the most applied in the literature analyzed is ReCiPe. For example, Uctug and Azapagic (66) consider a transport by lorry and ship and use the software CCalC to compute the impact over the categories of CML. Similarly, Nordin et al. (83) consider as input for SimaPro the 'unit of transportation' and calculate the impact across the indicators of ReCiPe. It is observed that the authors do not specify the meaning of the 'unit of transportation' adopted.

It is now analyzed the impact of the transportation phase in terms of cumulative energy demand and $CO_{2\text{-}eq}$ emission as a percentage with respect to the full life cycle. Figure 28 shows the values encountered in the 129 contributions included in the sample analyzed. The details of the plotted values and the respective sources are provided in Appendix A.2.

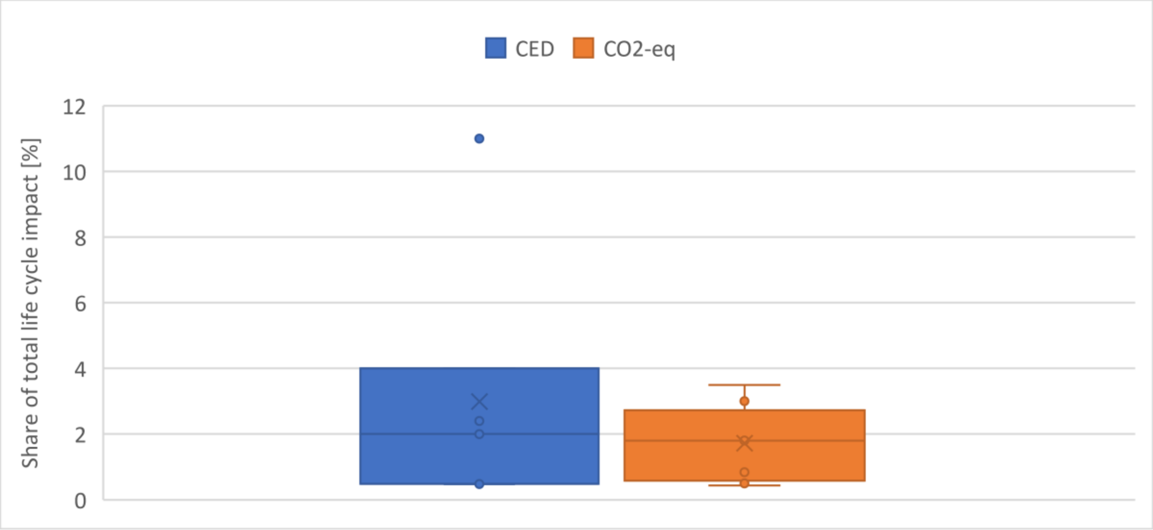

Figure 28: CED and $CO_{2\text{-eq}}$ emissions from the transportation phase in percentage with respect to the impact over the full life cycle (Own production).

It is observed that the impact of the transportation phase in terms of cumulative energy demand is always lower than 4.00% of the total impact over the life cycle except in one contribution providing the value of 11.00%. The outlier is indicated by Sumper et al. (150), considering transportation of modules and inverters by ship from Shanghai to Spain. The minimum value in Figure 28 is equal to 0.47% and is computed from data indicated in Wu et al. (86), where authors are assuming a transportation for 300 km in China.

The impact of the transportation phase in terms of $CO_{2\text{-eq}}$ emission ranges between 0.43% and 3.50% of the total impact over the life cycle. The minimum is mentioned by Nordin et al. (83), and authors are not specifying the distance covered nor the mode of transport chosen. The maximum is indicated by Fthenakis and Kim (145), assuming truck transportation in the USA.

2.2.5.5. Installation

It is observed in the literature analyzed that different definitions are adopted for the installation phase. Santoyo-Castelazo et al. (90) define it as the integration of the assembly structure, the electrical components, and the wiring for making the grid connection. It is detected that multiple authors include in the installation phase the transportation of components. For example, Jia et al. (143) define the installation phase as composed of modules transportation from the production factory to the installation site and the energy required during the installation of the system. A similar definition is applied by Sumper et al. (150) as well as by Szilágyi and Gróf (101). The latter include in the installation phase the site preparation, the transport of components to the installation site, and the energy carriers (diesel and electricity) consumption in the installation process.

In line with the different definitions encountered in the literature, the modeling approaches adopted vary depending on the assumptions made. Starting from the authors developing a tailored model instead of using an LCA software, it is observed that Hou et al. (132) compute the energy consumption of the system integration and construction phase as the product of the specific energy requirement of 0.255 kWh/W by the size of the PV system in watt. It is important to mention that the value of 0.255 kWh/W also includes the energy to manufacture BOS components and not only the energy needed to install the system. Considering the modeling approach to compute the $CO_{2\text{-eq}}$ emissions from the installation phase, it is observed that multiple authors apply a similar methodology, starting from the energy consumption of the installation process and considering the carbon intensity of the grid supplying the process. For example, Hou et al. (132) compute the emissions from the process of system integration and construction according to the following formula:

$$GHG = \frac{GHG_{grid} * E}{Q}$$

Where:

- GHG indicates the emissions generated during the system integration and construction process in $gCO_{2\text{-eq}}/kWh$.
- GHG_{grid} is the average grid carbon intensity, in $gCO_{2\text{-eq}}/kWh$. The authors apply the value of the Chinese public grid for a system manufactured and installed in China.
- E is the energy consumption of the system integration and construction process in kWh/W. As mentioned above, E is equal to 0.255 kWh/W and includes also the energy to manufacture BOS components and not only the energy needed to install the system.
- Q is the energy output per watt of the system in kWh/W.

Furthermore, Nicholls et al. (133) apply a similar procedure to the one described above: emissions are computed by multiplying the embedded energy of the system [GJ] by a factor representative of the grid carbon intensity [$kgCO_{2\text{-eq}}/kWh$]. The embedded energy comprehends the energy required to assemble the system.

As demonstrated in Paragraph 2.2.2.5, most contributions in the literature analyzed employ specific LCA software, such as SimaPro or GABI, to complete the analysis. In those cases, the approach to carry out the analysis do not employ a tailored model, as for example the one from Hou et al. (132) mentioned above. Instead, the analysis starts with the definition of the inventory of materials and energy consumed in the installation phase. The inventory represents the input for the software, that automatically computes the environmental impact (142). The environmental impact categories computed depend on the selected LCIA methodology: in Paragraph 2.2.2.3 it has been demonstrated that the most applied in the literature analyzed is ReCiPe. For example, Desideri et al. (152) compile the inventory of materials and energy consumed in the installation phase, including the land preparation activities, the installation of support structures, modules, and electrical components. SimaPro is the software used to compute the impact according to Eco-Indicator 99 methodology. Furthermore, Sumper et al. (150) model the installation phase of a rooftop PV system by considering the weight of the system lifted and the performance of the engine used, and SimaPro is the software used to compute the impact in terms of primary energy requirements and $CO_{2\text{-eq}}$ emissions. To conclude, it is observed that Jia et al. (140) model the installation phase as comprehensive of modules transportation and of a power consumption of 10 kWh/kW. SimaPro is the software employed to compute the impact categories of ReCiPe methodology (140).

The values of the impact of the installation phase encountered in the 129 contributions analyzed in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions as a percentage with respect to the impact of the full life cycle of the PV system are reported in Figure 29. The details of the plotted values and the respective sources are provided in Appendix A.2.

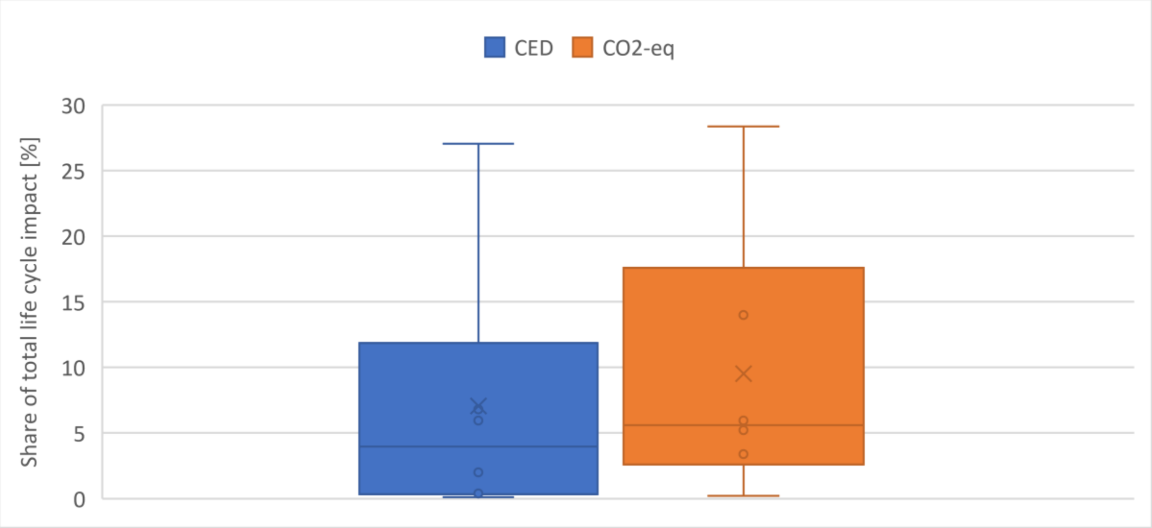

Figure 29: CED and $CO_{2\text{-eq}}$ emissions from the installation phase in percentage with respect to the impact over the full life cycle (Own production).

Considering the cumulative energy demand of the installation phase, Figure 29 demonstrates the high variability in the results encountered in the literature analyzed. This is justified by the different activities included in the installation phase by the different authors. The CED ranges from 0.10% to 27.06% of the total cumulative energy demand over the life cycle of the system. The minimum is

mentioned by Fthenakis and Kim (145) (153) and includes land preparation as well as integration of modules and BOS components. The maximum of 27.06% is computed from the results indicated in Li et al. (79) and refers to a BIPV application, namely a semi-transparent photovoltaic window. The authors include in the phase the assembly of PV modules and window as well as the installation of the window on the building.
The impact in terms of $CO_{2\text{-eq}}$ emissions of the installation phase shows a large variability, ranging from a minimum of 0.20% to a maximum of 28.36% of the impact over the full life cycle of the system. The minimum and the maximum are obtained from the same papers mentioned for the cumulative energy demand, namely Fthenakis and Kim (145) (153) and Li et al. (79).

2.2.5.6. Use

From the analysis of the literature, it emerges that the use phase comprehends the activities required during the operation and maintenance of the PV system. Some contributions only include in the use phase the replacement of components. Examples are given by Mustafa et al. (146) and by Ng and Mithraratne (154). The most common component considered for replacement is the inverter: given the lifetime of inverters usually set at 15 years, multiple authors consider a one-time replacement of the component over the lifetime of the PV system. Examples of authors adopting this hypothesis include Eskew et al. (37), Ng and Mithraratne (154), and Vellini et al. (103). Furthermore, Szilágyi and Gróf (101) indicate that the use phase includes not only the replacement of faulty components but also their transportation to site. It is observed that some authors, such as Hou et al. (132), include in the phase not only the replacement of components, but also the cleaning of modules. Contributions including more processes in the use phase comprehends the cleaning of modules, the replacement of components, the energy used in maintenance operation, and the electricity consumption in plant operations. An example of a paper applying this approach is Pamponet et al. (72). It is also observed that the activities included by Pamponet et al. (72) are in line with the recommendations from IEA methodological guidelines on LCA of photovoltaic (27).

Considering the modeling approaches for the use phase encountered in the literature, it is observed that they vary depending on the activities included in the phase. Starting from the authors developing a tailored model instead of using an LCA software, it is mentioned the modeling approach adopted by Hou et al. (132). The authors consider a replacement rate of components of 0.1%. Thus, the energy consumption during the use phase is obtained by multiplying the energy consumption during the PV system manufacturing process by the replacement rate of 0.1%, obtaining the value of 0.002 kWh/W. Considering the modeling approaches to compute the $CO_{2\text{-eq}}$, Hou et al. (132) consider the emissions from the use phase to be equal to 0.1% of the emissions due to PV system manufacturing, since the authors assume the energy consumption of the use phase to correspond to 0.1% of the energy consumption in the PV system manufacturing process. Furthermore, it is observed that Rajput et al. (155) compute the CO_2 emissions over the life cycle of the PV system by multiplying the embodied energy over the lifetime, inclusive of the energy requirements of the use phase, by a factor representative of the grid carbon intensity and transmission losses.

As demonstrated in Paragraph 2.2.2.5, most contributions in the literature analyzed employ specific LCA software, such as SimaPro or GABI, to carry out the analysis. In those cases, the approach to complete the LCA do not employ a tailored model, as for example the one from Hou et al. (132) mentioned above. The analysis starts with the definition of the inventory of materials and energy consumed in the use phase. The inventory represents the input for the software, that automatically computes the environmental impact (142). The environmental impact categories computed depend on the selected LCIA methodology: in Paragraph 2.2.2.3 it has been demonstrated that the most applied in the literature analyzed is ReCiPe. It is noticed that multiple authors model the use phase including the water consumption for cleaning and the replacement of components. For example, Yu et al. (25) adopt the software eBalance v4.7 and consider a weekly water consumption of 0.5 kg/m^2 for cleaning purposes, one replacement of inverters over the lifetime of the plant as well as an average replacement rate of 0.1% for the other components. Similarly, Pamponet et al. (72) employ the software SimaPro and model the use phase by considering the inverters to be replaced and their transportation by road and ship in terms of weight transported and distance covered, as well as the water consumption for cleaning. The selected impact assessment method is ReCiPe (72). Other authors do not consider the replacement of components and include in the use phase only the water consumption for cleaning and the energy usage during maintenance activities. For example, Nordin et al. (83) include an electricity consumption of 16000 kWh per month to power plant facilities, water consumption for cleaning activities as well as fuel consumption for grass cutting and transportation during maintenance activities. For water and fuel the authors do not provide the details of the consumption data, stating that they are modeled according to the utility bill from the system owner (83). The software employed is SimaPro and the impact of the use phase is evaluated according to ReCiPe indicators (83). Lastly, Jia et al. (143) model the use phase by assuming a water consumption of 20 l/m^2 for cleaning and an electricity consumption for reparation purposes of 0.2 kWh/kW. The authors do not specify whether the water or the power consumptions indicated represent weekly or monthly figures. The software employed is SimaPro and the LCIA methodology selected is ReCiPe (143).

The values of the impact of the use phase encountered in the 129 contributions analyzed in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions as a percentage with respect to the impact of the full life cycle are reported in Figure 30. The details of the plotted values and the respective sources are provided in Appendix A.2.

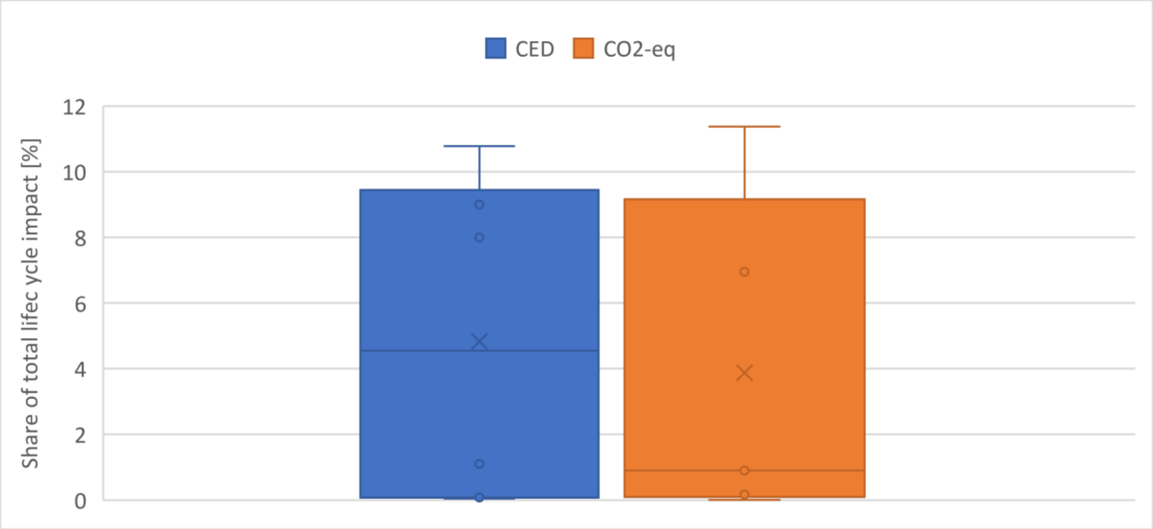

Figure 30: CED and $CO_{2\text{-eq}}$ emissions from the use phase in percentage with respect to the impact over the full life cycle (Own production).

Considering the cumulative energy demand of the use phase, it is observed a wide range of values, ranging from 0.04%, to 10.78% of the total CED over the life cycle of the system. The minimum and the maximum are mentioned by Jia et al. (143) and Nordin et al. (83), respectively. The former consider the water consumption for cleaning activities and the electricity consumption for maintenance activities, the latter model the use phase including the electricity consumption of 16000 kWh/month to power plant facilities, water consumption for cleaning, fuel for grass cutting and transportation during the operation and maintenance activities (143) (83).

A similar observation can be made for the impact in terms of $CO_{2\text{-eq}}$ emissions, ranging from a minimum of 0.01% in Santoyo-Castelazo et al. (90), to a maximum of 11.37% in Nordin et al. (83). The former do not specify the activities included in the use phase, the latter include the electricity consumption to power plant facilities, water for cleaning, fuel for grass cutting and transportation during the operation and maintenance activities (90) (83).

2.2.5.7. End-of-life

A common definition encountered in the literature considers the end-of-life phase as encompassing the deconstruction of the PV plant, the disposal and/or the recycling of components, as for example in Hou et al. (132). Yu et al. (25) adopt a similar definition and mention that the end-of-life phase is inclusive of the transportation of components from the installation location to the landfill or recycling facilities. As indicated by Luo et al. (156), end-of-life practices are still under development since most installations have been set up after 2010. Therefore, a lack of data is observed in the domain, leading some authors to ignore the process, as for example Rahman et al. (36). The end-of-life (EoL) of PV modules can occur through two pathways: disposal to landfill or recycling (77). The disposal to landfill is a common practice globally given the simplicity of the process, involving the transportation of used panels to a landfill (77). Considering the recycling, a scarce literature exists on the topic and on the evaluation of its impact on the environment (77). It is important to mention the inexistence of a common recycling method for PV modules (75). According to this observation, different authors adopt different methodologies when considering the recycling. For example, Ansanelli et al. (56) consider an innovative recycling process developed in the framework of the RESIELP[5] project, funded by the European Institute of Innovation and Technology. Clemons et al. (117) apply the recycling methodologies from Lunardi et al. (157). The contribution from the latter presents three different techniques for recycling: a mechanical process, a thermal process, and a chemical process. Briefly, the mechanical process is based on the extraction of the remaining materials from the modules, the thermal process is based on the controlled burning of ethylene vinyl acetate, assuming that glass can be recovered and cells can be reused for ingots growing, while the chemical process is based on the usage of organic solvents to recover glass and silicon (157).

In line with the different end-of-life scenarios possible, the modeling approaches encountered in the literature are various. Starting from the authors developing a tailored model instead of using an LCA software, it is observed that Hou et al. (132) model the impact of the end-of-life phase in terms of energy consumption by multiplying the energy requirement of 0.2 kWh/W by the size of the system. Lima et al. (61) model the primary energy consumption for the recycling phase starting from the specific factor of 25 MJ/m^2, contemplating only the glass recycling process. Zarzavilla et al. (158) compute the impact of the recycling process in terms of primary energy consumption by multiplying the factor of 2780 MJ/ton by the weight of modules. The source for the factor of 2780 MJ/ton is the contribution from

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[5] Recovery of Silicon and other materials from the End-of-life Photovoltaic Panels

Latunussa et al. (57), analyzing the recycling process developed within the 'Full Recovery End of Life Photovoltaic–- FRELP' project funded by the EU. The modeling approaches to compute the $CO_{2\text{-eq}}$ emissions arising from the end-of-life phase have been analyzed. Zarzavilla et al. (158) compute the $CO_{2\text{-eq}}$ emissions from the recycling process by multiplying the specific factor of 370 $kgCO_{2\text{-eq}}$/ton by the weight of modules. To conclude, it is mentioned the approach encountered in Lima et al. (61). The authors compute the $CO_{2\text{-eq}}$ emissions over the life cycle of the PV system starting from the energy requirements over the life cycle, inclusive of the recycling phase, in MJ/m^2, and by considering the area of the system, the grid conversion efficiency from primary energy to electricity and the grid carbon intensity (61).

As demonstrated in Paragraph 2.2.2.5, most contributions in the literature analyzed employ specific LCA software, such as SimaPro or GABI, to complete the LCA analysis. In those cases, the approach to complete the analysis does not employ a tailored model, as for example the one from Lima et al. (61) mentioned above. Instead, the analysis starts with the definition of the inventory of materials and energy consumed in the end-of-life phase. The inventory represents the input for the software, that automatically computes the environmental impact (142). The environmental impact categories computed depend on the selected LCIA methodology: in Paragraph 2.2.2.3 it has been demonstrated that the most applied in the literature analyzed is ReCiPe. Starting from the contributions considering the disposal scenario, some of them only consider the transportation of PV system's components to landfill, as for example Sierra et al. (159). Jia et al. (143) consider, in addition to the distance from the landfill of 1500 km, an electricity consumption of 0.1 kWh/kW to disassemble modules, and SimaPro is the software employed to compute the impact categories of ReCiPe (143). Moving to papers considering a recycling scenario, it is mentioned the modeling approach found in Kim et al. (80). The authors adopt the software SimaPro and consider the disposal and recycling ratio of each material based on data from pilot projects, and apply Korean national LCI databases to evaluate the environmental impact. Finally, Ansanelli et al. (56) compile the inventory of energy and materials for the recycling process investigated, and SimaPro is employed to compute the impact according to ReCiPe indicators.

It is observed in the literature that multiple scholars consider the environmental benefits arising from the end-of-life phase. Piasecka et al. (160) mention that recycling can reduce the environmental impact of the system over its life cycle. A similar observation is made by Fthenakis and Leccisi (23) and by Leccisi et al. (125). Similarly, in the review from Muteri et al. (12) it is mentioned that material recycling and the energy obtained from the combustion of some elements allow to reduce the environmental burdens compared to the landfill scenarios. As a matter of fact, the usage of recovered materials can be considered as a credit back to the system from avoided burdens (37) (161). Furthermore, it observed that multiple contributions consider the credits obtained from other processes than the recovered materials in the end-of-life phase. For example, Antonanzas et al. (75) adopt the software openLCA and compute the production of 12.75 MJ/kW of electricity from the incineration of plastics, reducing the total primary energy demand and the $CO_{2\text{-eq}}$ emissions over the life cycle of the system. Similarly, Latunussa et al. (57) employ the software SimaPro and estimate that the incineration of PV sandwich and plastic from cables generate 250 MJ of electricity and 500 MJ of thermal energy, thus reducing the primary energy demand of the recycling process considered.

The values of the impact of the end-of-life phase encountered in the 129 contributions analyzed in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions as a percentage with respect to the impact of the full life cycle are reported in Figure 31. It is remarked that in Figure 31 the values considering benefits from the recycling phase are not included, since they will be plotted in a dedicated chart (Figure 32). The details of the plotted values and the respective sources are provided in Appendix A.2.

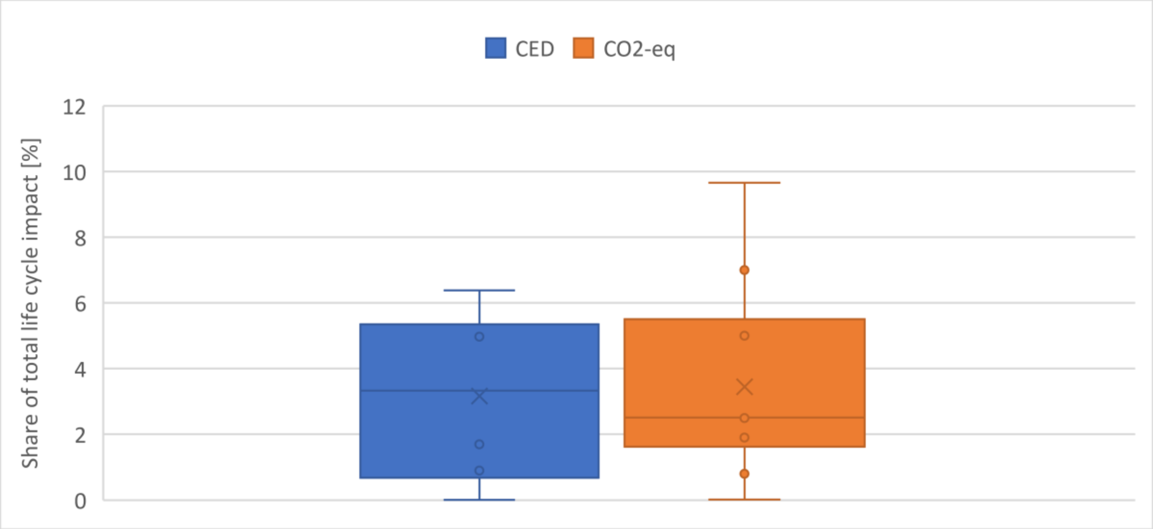

Figure 31: CED and $CO_{2\text{-eq}}$ emissions from the end-of-life phase in percentage with respect to the impact over the full life cycle (Own production).

The impact in terms of cumulative energy demand of the end-of-life phase ranges between 0.02% and 6.38% of the total requirements over the life cycle. The minimum is cited by Nordin et al. (83), where authors are only considering the transport of components to landfill. The maximum is computed from the results indicated in Held and Ilg (62), where it is considered the recycling of CdTe modules according to First Solar’s process.

The $CO_{2\text{-eq}}$ emissions of the end-of-life phase range between 0.01% and 9.66% of the total emissions over the life cycle. The minimum is encountered in the contribution from Nordin et al. (83), assuming only transportation of PV components to the nearest landfill located 17.4 km away from the plant. The maximum is found in Hou et al. (132), where the authors are modeling the end-of-life phase considering the average Chinese industry data for the energy consumption during the recycling process.

The values of the benefits from the end-of-life phase encountered in the 129 contributions analyzed in terms of cumulative energy demand and $CO_{2\text{-eq}}$ emissions as a percentage with respect to the impact of the full life cycle are reported in Figure 32. The details of the plotted values and the respective sources are provided in Appendix A.2.

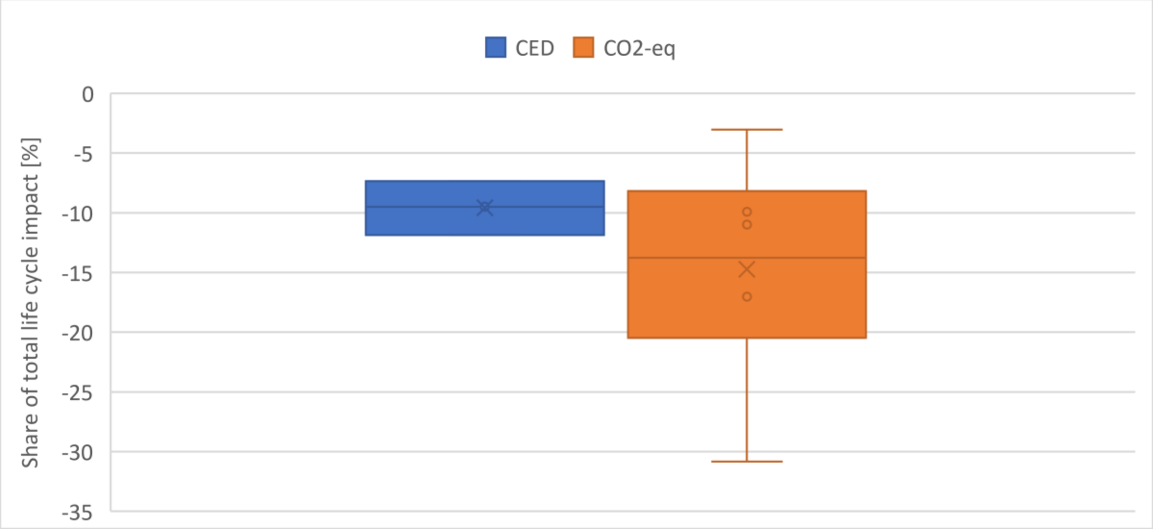

Figure 32: CED and $CO_{2\text{-eq}}$ emissions reduction from the benefits from end-of-life phase in percentage with respect to the impact over the full life cycle (Own production).

The benefits due to the end-of-life phase in terms of cumulative energy demand range between -7.36% and -11.87% of the total CED of the system analyzed. The first value is computed from the results indicated in Held and Ilg (62), where the scholars are considering the benefits from glass and copper recycling and from incineration. The benefits are computed with respect to the cumulative energy demand over the full life cycle of a CdTe ground-mounted PV system. The value of -11.87% is computed from data reported in Latunussa et al. (57), where the authors are considering the credits from the incineration of PV sandwich layers and cables. The higher absolute value can be justified by the fact that the mentioned authors only include within the boundaries of the analysis the recycling process, so that benefits from end-of-life cover a larger share of the total impact.

Considering the $CO_{2\text{-eq}}$ emissions, benefits due to the end-of-life phase range from -3.03% to -30.83% of the total emissions of the system analyzed. The first value is computed from the results indicated in Antonanzas et al. (75), where the scholars consider the benefits due to electricity generation from plastics incineration. The second value, equal to a 30.83% reduction, is estimated from a chart in the paper from Eskew et al. (37), where the authors consider the credits due to recycled materials, namely steel, aluminum, and plastics.

2.3. Gaps identified in the literature

The gaps identified in the literature analyzed are here recapped. The gaps are presented in the same order as their identification in the previous section.

The first gap identified is the limited usage of high-quality data, in particular referring to primary and updated data. In Paragraph 2.2.2.2 it has been demonstrated that 52 out of 129 contributions do not use primary data as a source. In addition, it has been demonstrated the common usage of outdated sources to compile the life cycle inventory. The observations are confirmed by selected scholars: Muteri et al. (12) observe a shortage of primary data in the contributions analyzed, and Muller et al. (74) mention that current LCA studies are often based on outdated inventories. The gap is considered relevant for two reasons. First, the different quality of inventory data is an issue making comparison among LCA studies difficult (69). Second, the use of outdated inventory data can bring to divergent conclusions for scholars and decision makers (76), given the discrepancies between databases and real-world data, while technologies are quickly evolving (77).

The second gap identified is the limited usage of a combination of metrics evaluating more than one environmental problem. For example, only 3 out of the 129 contributions analyzed provide results for all the four most common metrics (CED, EPBT, CO_2PBT, GWP). The observation is confirmed by selected scholars. Rashedi and Khanam (73) observe that a common limitation of the studies analyzed consists in addressing a limited set of indicators. Also, Chatzisideris et al. (88) highlight the importance of covering multiple environmental impact indicators, and mention as a future improvement for LCA practitioners the inclusion of results for more environmental issues. The gap is considered relevant since the combination of more indicators can help in identifying trade-offs and taking more informed decisions (88).

The third gap identified is the limited coverage of the full life cycle, including the end-of-life phase, within the boundaries of the analysis. In the sample of 129 papers analyzed, only 31 contributions include all the six phases composing the life cycle included in the framework presented in Paragraph 2.2.2.4, while the end-of-life is the least included phase, appearing in only 64 contributions. The observation is confirmed by selected scholars. In the review from Chatzideris et al. (88) it is shown the limited number of studies covering the full life cycle, and in the review from Gerbinet at al. (47) it is mentioned that the end-of-life phase is often not included within the boundaries of the analysis, even if it can have a significant influence on results. The gap is relevant given the risk of burden-shifting across phases if the full life cycle is not covered (88), and the importance of the end-of-life phase for the future sustainability of PV technologies (98) (99).

The fourth gap is represented by the limited inclusion of scenarios considering different locations for the manufacturing of the various components composing the PV system. It has been demonstrated that only 5 contributions within the sample analyzed consider different locations for the manufacturing of modules and BOS components. The gap is considered relevant since the inclusion of different geographies for the manufacturing of the various components create scenarios more representative of real market dynamics, since in most cases modules and BOS components are not imported from the same country (105).

The fifth gap identified is the scarcity of contributions providing a comparison across multiple modules technologies. It has been demonstrated that only 11 out of the 129 contributions in the sample include the five main PV technologies (monocrystalline, multicrystalline, CI(G)S, CdTe, a-Si) within the analysis. A similar observation is made by selected scholars: Rashedi and Khanam (73) state in their paper from 2020 the absence of contributions comparing the four most common PV technologies by ReCiPe methodology. The gap is considered relevant since the comparisons of PV technologies can provide useful industrial and policy implications. Furthermore, the importance of comparing different technologies in the same LCA study is given by the fact that results of an LCA analysis are intrinsically dependent on the assumptions taken, so that comparing results from different studies is not equivalent to the comparison of different technologies within the same LCA study.

2.4. Research questions

The previous section presented the gaps identified in the literature. Thus, the gaps tackled by the current thesis are selected below, and the corresponding research questions (RQ) are presented.

The first gap, represented by the limited usage of primary and updated data, is not directly tackled by the current thesis. This is due to the limitations encountered in gathering primary data, for example by contacting manufacturers, as well as in accessing updated LCI databases. For example, a license costing almost 4k EUR is required to access to the most recent Ecoinvent database (162). Given the relevance of the gap and the fact of not being tackled by the current thesis, it is important to mention it as an avenue for future research: future LCA studies can consider the influence of primary and updated data on results.

The second gap, represented by the limited usage of a combination of metrics evaluating more than one environmental problem, is tackled by the current thesis. The objective consists in answering the corresponding research question:

> RQ1: What are the trade-offs arising when multiple metrics evaluating more than one environmental problem are considered and how the usage of multiple metrics can help in taking decisions?

The third gap is represented by the limited coverage of the full life cycle, comprehensive of the end-of-life phase, within the boundaries of the analysis. The gap is tackled by the current thesis. The objective consists in providing an answer to the corresponding research question:

> RQ2: What is the influence of the different phases composing the life cycle on the environmental impact of PV technologies?

The fourth gap consists in the limited inclusion of scenarios considering different locations for the manufacturing of the various components of the PV systems. The gap is tackled by the current thesis. In particular, the objective consists in answering the corresponding research question:

> RQ3: How does the environmental impact of PV technologies change depending on the manufacturing locations of the different components of the system?

The fifth gap consists in the scarcity of contributions including a comparison across multiple modules technologies. Tackling this gap is considered within the scope of the current thesis, with the objective of answering to the corresponding research question:

> RQ4: How does the environmental impact change depending on the PV technology considered?

The current thesis aims at answering in the most exhaustive manner possible the identified research questions. The next chapter will present the methodology adopted.

3 Methodology

3.1. Introduction

The objective of the thesis is to answer in the most exhaustive manner possible the research questions identified in Section 2.4. The methodology adopted to answer the research questions consists in performing an LCA analysis of PV technologies. In the literature review, it was detected the limited number of contributions developing tailored models to complete the LCA, as well as the limitations of existing tailored models, for example in terms of coverage of the full life cycle and of inclusion of multiple PV technologies. Furthermore, it was observed that tailored models are considered of simpler use than LCA software and permit to a wider range of users to complete a sustainability assessment on a spreadsheet application (101). Given the mentioned findings from the literature review, the LCA will be completed by using a tailored evaluation framework. Accordingly, the methodological process to complete the LCA articulates into the development of the evaluation framework and its subsequent application.

3.2. Evaluation framework development

The evaluation framework will be developed with the aim of addressing the identified literature gaps. For example, given the shortage of studies covering the full life cycle, the model will enable to assess the cradle-to-grave environmental impact of PV technologies. The development of the evaluation framework is presented in detail in Chapter 4.

3.3. Evaluation framework application

Once the evaluation framework is developed, the second step to complete the LCA consists in its application. The application of the evaluation framework is detailed in Chapter 5. Briefly, the application of the model consists in three steps. First, the scenarios to be examined are selected. Second, the results obtained are presented and analyzed. Third, sensitivity analyses on a selection of parameters are completed, to discover their influence on results.

4 Evaluation framework development

4.1. Evaluation framework overview

In the current section it is provided an overview of the evaluation framework.

The evaluation framework assesses the cradle-to-grave impact of the most common PV technologies. The PV technologies considered are monocrystalline, multicrystalline, CdTe, a-Si, CIS, OPV. The first five are the technologies holding the highest market share, as presented in Section 1.2, and OPV is added to have a comparison with an emerging technology, defined as the fastest advancing PV technology by the IEA (15). The model performs computations on ground-mounted installations connected to the grid. As observed in Chapter 1, grid-connected ground-mounted applications represent the highest share of the cumulative installed PV capacity. The life cycle is divided into the six phases presented in the literature review chapter: modules manufacturing, BOS manufacturing, transportation, installation, use, end-of-life. The impact is evaluated in terms of the following indicators: cumulative energy demand (CED), global warming potential (GWP), energy payback time (EPBT), CO_2 payback time (CO_2PBT). It is observed that the indicators selected correspond to two of the most pressing environmental problems, represented by greenhouse gases emissions and energy consumption, and are among the most adopted metrics in LCA studies of PV technologies, as presented in the literature review. The evaluation framework will be developed using the literature as the main source of inventory data. The reason for this choice is twofold. First, as presented in the literature review, the choice of the literature as the source of data is common for LCA practitioners, and also permits to discover the main choices made by other scholars. Second, LCI commercial databases require a license to obtain access. For example, a license worth almost 4k EUR is necessary to use Ecoinvent, the most famous LCI database (162) (163). Each of the six phases composing the lifecycle as well as the section covering the electricity production is presented leveraging on the knowledge gathered in the literature review chapter.

The current chapter presents in detail the development of the evaluation framework. The following Section 4.2 covers the approach adopted to model the electricity production.

4.2. Electricity production

The evaluation framework computes the electricity generated by the PV system over its lifetime. An approach considering the performance ratio and the degradation rate is adopted. The electricity generated over the lifetime of the PV system is obtained thanks to Equation 1 (74) (164).

Equation 1:

$$Electricity\,produced\,during\,lifetime[kWh] = \sum_{y=1}^{T[Year]} (1 - DR[\%])^{y} * I\left[\frac{kWh}{m^2 * Year}\right] * A[m^2] * \eta[\%] * PR[\%]$$

Where:

- *Electricity produced during lifetime* is the electricity produced during the lifetime of the PV system in kWh.
- *T* is the lifetime of the PV system in years. It depends on the PV technology considered. The values of the lifetime applied in the model are indicated in Table 5.
- *DR* is the mean annual percentage degradation rate. It depends on the PV technology considered. The values of the degradation rate applied in the model are indicated in Table 5.
- *I* is the specific average annual solar irradiation [kWh/(m^2*y)]. In the model developed, it depends on the country where the PV system is installed.
- *A* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific area [m^2/kW] applied in the model are indicated in Table 5.
- η is the module efficiency under standard testing conditions. It depends on the PV technology considered. The values of the module efficiency applied in the model are indicated in Table 5.
- *PR* is the unitless performance ratio, defined as the ratio between the system's final yield and its ideal yield. The values of the performance ratio applied in the model are indicated in Table 5

The literature is analyzed to gather the necessary data and define the parameters needed to perform Equation 1. Starting from the lifetime, the value of 30 years is adopted for first generation technologies, according to data from the IEA (27) (165). In line with data from Liu and van den Bergh (110), the same lifetime of 30 years is applied for second generation technologies. As a matter of fact, in the literature review chapter it has been demonstrated that the lifetime of 30 years is the most frequently applied for first- and second-generation technologies. As shown in Paragraph 2.2.4.3, emerging technologies are characterized by a shorter lifetime. It is applied in the model the lifetime of 10 years for OPV modules (127).

Considering the degradation rate, IEA Guidelines suggest to adopt the value of 0.7%/year for mature technologies (27). The value of 0.7%/year is thus applied for first generation technologies. For CdTe and CIS modules technologies, it is applied the value of 1%/year found on the European Commission report on PV systems published in 2020 (24). The degradation rate of a-Si modules is not indicated in the cited report. Nevertheless, the value is gathered from Piliougine et al. (166), that analyze the degradation rate of a-Si technology and indicate the value of 1.12%/year. Finally, the degradation rate of OPV technology considered in the model is 1.38%/year (161).

The country-specific values of the irradiation are obtained from the most updated database published from the World Bank (167).

Considering the specific area [m^2/kW] of modules, values for all technologies except OPV are gathered from the same source, namely the LCI report from ESU-services (168). ESU-services is a Swiss company that significantly contributed to the creation of the Ecoinvent database, having elaborated over 900 of the 4000 life cycle inventory datasets included in Ecoinvent version 2.2 (169). The values of the specific areas of modules in m^2/kW applied in the evaluation framework are equal to 7.14 for monocrystalline, 7.35 for multicrystalline, 8.55 for CdTe, 9.26 for CIS, and 15.38 for a-Si. The specific area of OPV modules is gathered from Tsang et al. (170) and is equal to 20 m^2/kW.

The modules efficiencies are collected from the recent IEA LCI Report 2020, and are equal to 19.5% for monocrystalline, 18% for multicrystalline, 18% for CdTe, and 16% for CIS (171). It is observed that the Photovoltaics Report from the Fraunhofer Institute indicates similar values of efficiencies for first generation and CdTe modules (17). The efficiency of a-Si modules applied in the model is equal to 7.5% (110). The value applied is confirmed by the review from Rabaia et al. (172), indicating that the efficiency of a-Si technology is equal to 8%. As observed in Paragraph 2.2.4.1, the average efficiency of OPV technology is lower compared to first- and second-generation technologies. The module efficiency for the OPV technology applied in the model is collected from Tsang et al. (170) and is equal to 5%.

Considering the performance ratio, IEA Guidelines on LCA suggest to adopt the value of 0.8 for ground-mounted installations (27). The suggested value is confirmed by multiple contributions from the literature, such as Espinosa Martinez et al. (173), applying the value of 0.8 for a ground-mounted system adopting OPV technology. A performance ratio of 0.8 is thus applied in the model for all technologies.

Table 5 provides a recap of the values of the lifetime, degradation rate, specific area, module efficiency, and performance ratio applied in the evaluation framework for the six PV technologies considered.

Technology	Lifetime [Year]	Degradation rate [%/Year]	Specific area [m^2/kW]	Module efficiency [%]	Performance ratio [-]
Monocrystalline	30	0.7	7.14	19.5	0.80
Multicrystalline	30	0.7	7.35	18	0.80
CdTe	30	1	8.55	18	0.80
CIS	30	1	9.26	16	0.80
a-Si	30	1.12	15.38	7.5	0.80
OPV	10	1.38	20	5	0.80

Table 5: Values of parameters for the selected technologies (Own production).

4.3. Modules manufacturing

The modules manufacturing phase is defined in the model as encompassing raw materials extraction, processing, and modules assembling (135). As shown by Jia et al. (140) and by Mehedi et al. (135), the frame manufacturing should be included in the phase. It is discovered that not all modules technologies are framed: in the Report on Product Environmental Footprint Category Rules from the European Commission, it is shown that 95% of crystalline silicon modules installed in Europe and the totality of CIS modules are framed, while CdTe modules are unframed (174). It is observed that this information is in line with the book from Urbina (16), mentioning that an aluminum frame is still included by most manufacturers of first generation modules, as well with the LCI Report from ESU-services, observing that CdTe modules are frameless (168). Consequently, monocrystalline, multicrystalline, and CIS modules are considered framed in the evaluation framework, while CdTe modules are frameless. As for a-Si modules, they are considered framed in the model according to data from ESU-services LCI Report (168). Finally, as mentioned by Espinosa Martinez et al. (173), OPV modules do not need a frame and are thus considered unframed in the model.

The approach considered to evaluate the impact in terms of primary energy consumption of the modules manufacturing phase is similar to the one observed in Rahman et al. (36), that is to say starting from the primary energy requirement per unit of surface during the manufacturing process and multiplying it by the modules' area. The values of the cumulative energy demand of the modules manufacturing phase for the six PV technologies considered are gathered from the literature. For monocrystalline modules, the values of the cumulative energy demand for the manufacturing phase observed in the literature are characterized by a wide variance, ranging from a minimum of 1949 MJ/m², estimated from a chart included in Fthenakis and Leccisi (23) to a maximum of 6829 MJ/m² cited in Garcia-Valverde et al. (128). Figure 33 shows the values encountered in the sample of 129 contributions analyzed in the literature review chapter. The details of the plotted values and the respective sources are provided in Appendix A.3.

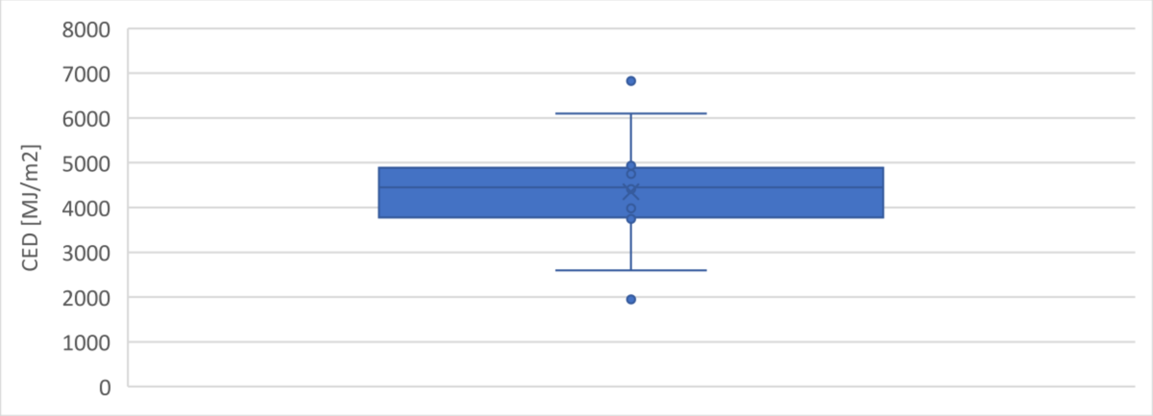

Figure 33: Values encountered in the literature for the cumulative energy demand for monocrystalline modules manufacturing (Own production).

In the model it is applied the value of 4490 MJ/m² from Soares et al. (134). The value refers to the manufacturing of framed monocrystalline modules according to the definition provided in the contribution and the corresponding process checked in the database used by the authors, namely Ecoinvent 3.3 (175). The value applied is in line with other recent contributions such as Liu and van den Bergh (110), published in 2020 and indicating a value close to 4415 MJ/m² in a chart, as well as Ludin et al. (38), published in 2021 and providing the value of 4750 MJ/m². It is also observed in Figure 33 that the value applied in the model is close to the average of the values encountered in the literature.

Similarly, the values of the cumulative energy demand for the manufacturing of multicrystalline modules encountered in the literatures vary widely, ranging from a minimum of 1816 MJ/m² estimated from a chart in Fthenakis and Leccisi (23), to a maximum of 4600 MJ/m² mentioned in Akinyele (84). The values encountered in the sample of 129 contributions analyzed in the literature review chapter are plotted in

Figure 34. The details of the plotted values and the respective sources are provided in Appendix A.3.

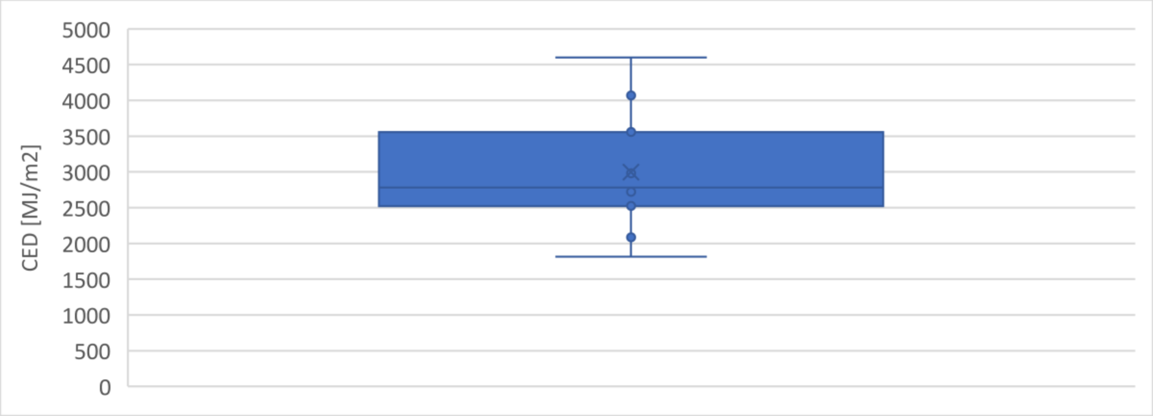

Figure 34: Values encountered in the literature for the cumulative energy demand for multicrystalline modules manufacturing (Own production).

The value of 3559 MJ/m² from Soares et al. (134) is applied in the model, since positioned between the most recent estimates encountered in the literature, such as 2982 MJ/m² estimated from a chart included in the paper from Liu and van den Bergh (110), published in 2020, and 4070 MJ/m² from Ludin et al. (38), published in 2021. The value applied refers to the manufacturing of framed multicrystalline modules according to the definition provided in the contribution and the corresponding process checked in the database used by the authors, namely Ecoinvent 3.3 (175).

Considering the manufacturing of CdTe modules, a paper published in 2010 indicates a cumulative energy demand equal to 2031 MJ/m² (176). A more recent paper from 2021 published by Leccisi and Fthenakis indicates a significantly lower value, estimated from a chart as equal to 857 MJ/m² (122). Figure 35 shows the distribution of the values encountered in the sample of 129 contributions analyzed in the literature review chapter. The details of the values plotted in Figure 35 and the respective sources are provided in Appendix A.3.

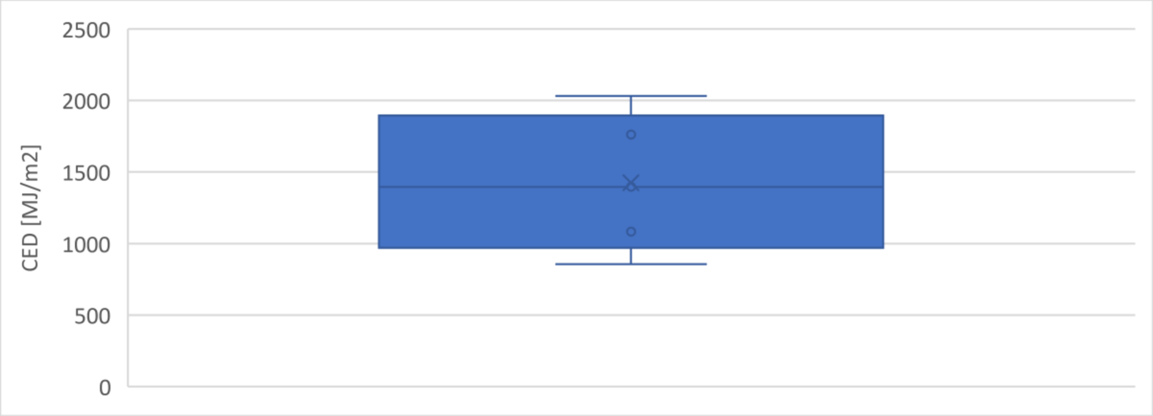

Figure 35: Values encountered in the literature for the cumulative energy demand for CdTe modules manufacturing (Own production).

In the model it is considered the value of 1083 MJ/m² for the manufacturing of unframed CdTe modules (109). The selected value lies between the most recent data points included in Figure 35, such as 1396 MJ/m², estimated from a chart included in a paper published in 2020 by Liu and van den Bergh (110), and the value of 857 MJ/m² estimated from the paper published in 2021 by Leccisi and Fthenakis (122). Considering the manufacturing of CIS modules, the values of the cumulative energy demand encountered in the literature range from 1105 MJ/m² in Ito et al. (151) to 3107 MJ/m² mentioned in Garcia-Valverde et al. (128). Figure 36 shows the distribution of the values encountered in the sample of 129 contributions analyzed in the literature review chapter. The details of the values plotted in Figure 36 and the respective sources are provided in Appendix A.3.

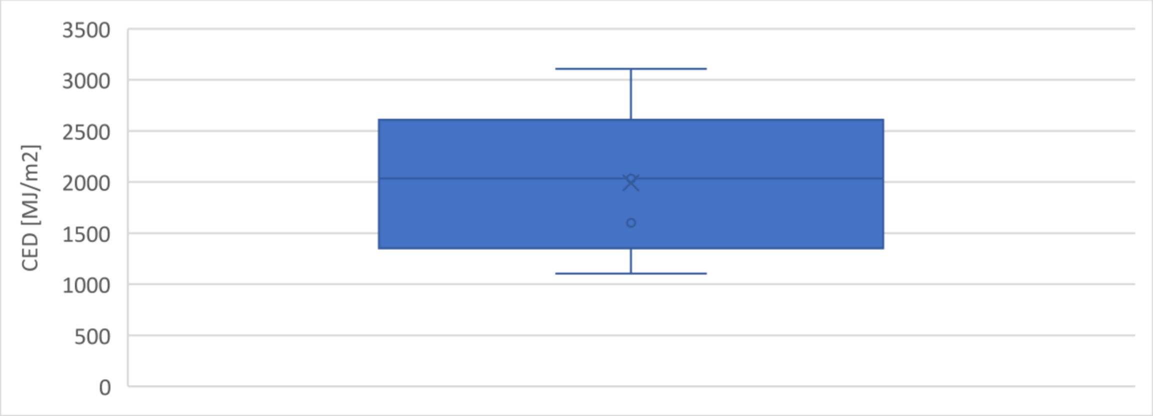

Figure 36: Values encountered in the literature for the cumulative energy demand for CIS modules manufacturing (Own production).

In the evaluation framework it is applied the value of 2109 MJ/m² from Soares et al. (134). The value refers to the manufacturing of framed CIS modules according to the definition provided in the contribution and the corresponding process checked in the database used by the authors, namely Ecoinvent 3.3 (175). It is observed that the value is very similar to the one mentioned by Ito et al. (109) of 2035 MJ/m², and is close to the average of the values found in the literature, as shown in Figure 36.

Considering the manufacturing of a-Si modules, the values of the cumulative energy demand encountered in the literature range from a minimum of 847 MJ/m² cited by Kittner et al. (113), to a maximum of 1550 MJ/m² estimated from a chart in the paper from Liu and van den Bergh (110). The details of the values encountered in the sample of 129 contributions analyzed in the literature review chapter and plotted in Figure 37 as well as the respective sources are provided in Appendix A.3.

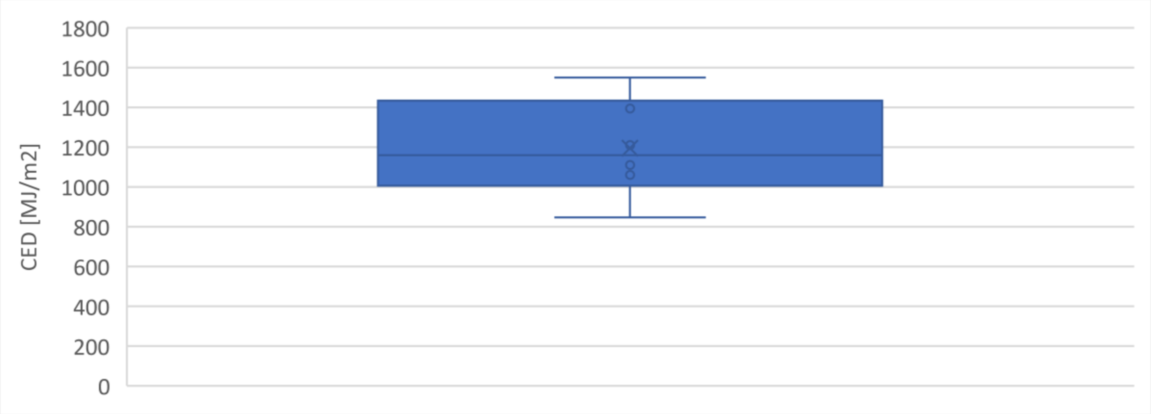

Figure 37: Values encountered in the literature for the cumulative energy demand for a-Si modules manufacturing (Own production).

In the model it is applied the value from Soares et al. (134) of 1394 MJ/m². The value refers to the manufacturing of framed a-Si modules, according to definition provided in the contribution and the corresponding process checked in the database used by the authors, namely Ecoinvent 3.3 (175). It is observed that the selected value is one of the most recent of those included in Figure 37, and is close to the estimate from the recent paper from Liu and van den Bergh (110), published in 2020 and indicating in a chart a value close to 1550 MJ/m².

Considering the last technology included in the model, a paper published in 2010 analyzing the manufacturing of OPV modules on a laboratory scale shows the value of 2800 MJ/m² (176) for the cumulative energy demand. A more recent paper published in 2015 from Tsang et al. (96) indicates the value of 130 MJ/m² to manufacture unframed OPV cells and shows in a chart the similarities with most of the recent literature. A very similar value of the cumulative energy demand to manufacture unframed OPV modules equal to 110 MJ/m² from Hengevoss et al. (177) is applied in the evaluation framework.

Table 6 provides a summary of the values applied in the model for the cumulative energy demand of the modules manufacturing phase of the six PV technologies considered.

Technology	Specific CED [MJ/m^2]
Monocrystalline	4490
Multicrystalline	3559
CdTe	1083
CIS	2109
a-Si	1394
OPV	110

Table 6: Specific cumulative energy demand in modules manufacturing phase (Own production).

The cumulative energy demand of the modules manufacturing phase is obtained thanks to Equation 2.

Equation 2:

$$E_{Modules\ manufacturing}[MJ] = Specific\ CED\ Modules\ manufacturing\left[\frac{MJ}{m^2}\right] * Area[m^2]$$

Where:

- *Specific CED Modules manufacturing* is the PV technology-specific value of the cumulative energy demand of the modules manufacturing process in MJ/m^2. The values applied in the model are indicated in Table 6.
- *Area* indicates the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific area [m^2/kW] applied in the model are indicated in Table 5.

Muller et al. (74) observes that electricity is the main driver of the $CO_{2\text{-eq}}$ emissions from first-generation modules manufacturing, so that it is reasonable that the carbon intensity of the grid supplying the manufacturing process significantly affect the $CO_{2\text{-eq}}$ emissions (178). Similarly, in the contribution from Held and Ilg (62) focusing on CdTe technology, it is observed that the main contribution to the $CO_{2\text{-eq}}$ emissions of the modules manufacturing process is due to the electricity consumption. Also, for OPV modules the GHG emissions due to the manufacturing process are highly dependent on the carbon intensity of the electricity used (128).

Thus, an approach similar to the one observed in Hou et al. (132) and presented in the literature review chapter is adopted to compute the $CO_{2\text{-eq}}$ emissions starting from the energy needed during the manufacturing phase and the grid carbon intensity. It is also observed that the chosen approach is similar to the one encountered in Lima et al. (61), computing the life cycle emissions of the PV system by multiplying the primary energy needed over the life cycle, comprehensive of the modules manufacturing process, by the grid carbon intensity of the country of production and the conversion efficiency from primary energy to electricity. As observed in the IEA Special Report on PV Supply Chain (32), the different steps of the modules manufacturing process can happen in different countries. It is considered in the current study, in line with multiple scholars such as Serrano-Lujan et al. (102) and Lima et al. (61), that the modules manufacturing process is completed in one single country. It is acknowledged that the assumption of considering only one country for the whole modules manufacturing process is not fully reflecting the complexity of PV supply chain, and a future improvement of the current evaluation framework can include a higher level of granularity, permitting to consider different countries for the various modules manufacturing steps. The $CO_{2\text{-eq}}$ emissions from the modules manufacturing phase are obtained according to Equation 3.

Equation 3:

$$\begin{aligned} CO_{2-eq}\ Emissions\ Modules\ manufacturing\left[gCO_{2-eq}\right] \\ = E_{Modules\ manufacturing}[MJ] \\ * Grid\ carbon\ intensity\ modules\left[\frac{gCO_{2-eq}}{kWh}\right] \\ * Grid\ conversion\ efficiency[\%] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right] \end{aligned}$$

Where:

- $E_{Modules\ manufacturing}$ is the cumulative energy demand for the modules manufacturing phase [MJ] computed according to Equation 2.
- *Grid carbon intensity modules* is the grid carbon intensity of the country where PV modules are manufactured [$gCO_{2\text{-eq}}$/kWh]. The country-specific grid carbon intensities applied in the model are obtained from the most recent database published on the website Our world in data (179), providing values for the year 2021. It is observed that the database is compiled with data from Ember and BP publications (179).
- *Grid conversion efficiency* represents the grid conversion efficiency from primary energy to electricity. Fthenakis and Leccisi (23) consider the value of 30%, representative of conventional electricity systems. Similarly, the review from Bhandari et al. (180) assumes the factor of 35% for harmonization if not

better specified in the study. In line with the mentioned contributions, in the model is applied the factor of 35%.

The $CO_{2\text{-eq}}$ emission intensity of the modules manufacturing phase is obtained by ratio of the $CO_{2\text{-eq}}$ emissions released and the electricity produced over the lifetime, as shows in the following formula:

$$CO_{2-eq}\ Emission\ intensity\ Modules\ manufacturing\left[\frac{gCO_{2-eq}}{kWh}\right] = \frac{CO_{2-eq}\ Emissions\ Modules\ manufacturing\left[gCO_{2-eq}\right]}{Electricity\ produced\ during\ lifetime[kWh]}$$

Where:

- *$CO_{2\text{-eq}}$ Emissions Modules manufacturing* represents the $CO_{2\text{-eq}}$ emissions from the modules manufacturing phase computed by Equation 3.
- *Electricity produced during lifetime* is the electricity produced [kWh] over the lifetime of the system computed by Equation 1.

4.4. BOS manufacturing

The BOS manufacturing phase is defined in the model as corresponding to the manufacturing of structural and electrical components different than PV modules. The modeling approach considered is similar to the one found in in Wu et al. (86), that is to say computing the primary energy requirement to manufacture BOS components starting from a factor in MJ/kW for the inverter and a factor in MJ/m^2 for the remaining BOS components. The book by Urbina confirms that the energy demand of inverters strongly depends on their nominal power (16), and that for BOS structural components the unit of measure MJ/m^2 is more meaningful for LCA studies, since the unit MJ/kW will strongly depend on the efficiency of the PV modules considered. Antonanzas et al. (75) mention that results from Mason et al. (181) on the embedded energy of BOS components have been extensively used in the literature and are widely accepted in the field. The contribution from the latter is selected as the source of data also because it provides a breakdown of the primary energy requirements for the various BOS components, and this is observed to be rare in the sample analyzed. From Mason et al. (181), the value of 1321 MJ/kW is set in the model for the cumulative energy demand to manufacture the inverter. It is observed that similar values can be found in the review from Peng et al. (85). The inverter is sized considering an inverter loading ratio equal to 1, as found for example in Beylot et al. (107), in Koulompis et al. (149), and in Nicholls et al. (133). Considering the primary energy requirements in MJ/kW and the area in m^2/kW of the system from data in Mason et al. (134), the value of 299 MJ/m^2 is estimated for the cumulative energy demand to manufacture BOS components different than the inverter, namely the mounting structures, the cabling, and the equipment for grid connection. The mentioned specific energy requirements for BOS components manufacturing are considered constant for the different PV technologies (122) (102). The cumulative energy demand of the BOS manufacturing phase is computed as per Equation 4.

Equation 4:

$$E_{BOS\ manufacturing}[MJ] = Specific\ CED\ BOS\ other\left[\frac{MJ}{m^2}\right] * Area[m^2] + Specific\ CED\ inverter\left[\frac{MJ}{kW}\right] * Capacity[kW]$$

Where:

- *Specific CED BOS other* represents the cumulative energy demand to manufacture the BOS components different than the inverter. It is equal to 299 MJ/m^2 in the model.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.
- *Specific CED inverter* represents the cumulative energy demand to manufacture the inverter. It is equal to 1321 MJ/kW in the model.
- *Capacity* represents the power of the PV system in kW.

As observed in Muller et al. (74), the electricity mix of the country of manufacturing is an important driver of the environmental impact of BOS components: the authors mention that the carbon footprint of BOS components more than double when the electricity mix changes from the European to the Chinese one. Thus, an approach similar to the one observed in Hou et al. (132) and presented in the literature review chapter is applied, computing the $CO_{2\text{-}eq}$ emissions from the manufacturing of BOS components by multiplying the energy consumed in the manufacturing process by the grid carbon intensity. It is observed that the different BOS components can be manufactured in different countries. For example, in Eskew et al. (37), mounting structure is manufactured in Australia and inverters in India, whereas in Ito et al. (109) structural components are produced in Morocco, while inverters and other electrical equipment are manufactured in France. A similar approach is adopted in the model, considering one country for the inverter manufacturing and one country for the manufacturing of the remaining BOS components. Thus, the $CO_{2\text{-}eq}$ emissions from the BOS manufacturing phase are computed according to Equation 5.

Equation 5:

$$\begin{aligned}
&CO_{2-eq}\ Emissions\ BOS\ manufacturing\left[gCO_{2-eq}\right]\\
&\qquad = Specific\ CED\ BOS\ other\left[\frac{MJ}{m^2}\right] * Area\left[m^2\right]\\
&\qquad * Grid\ conversion\ efficiency[\%]\\
&\qquad * Grid\ carbon\ intensity\ BOS\ other\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right]\\
&\qquad + Specific\ CED\ inverter\left[\frac{MJ}{kW}\right] * Capacity[kW]\\
&\qquad * Grid\ conversion\ efficiency[\%]\\
&\qquad * Grid\ carbon\ intensity\ inverter\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right]
\end{aligned}$$

Where:

- *Specific CED BOS other* represents the cumulative energy demand to manufacture the BOS components different than the inverter. It is equal to 299 MJ/m^2 in the model.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.
- *Specific CED inverter* represents the cumulative energy demand to manufacture the inverter. It is equal to 1321 MJ/kW in the model.
- *Capacity* represents the power of the PV system in kW.
- *Grid conversion efficiency* is the efficiency of the grid in the conversion from primary energy to electricity. In the model, it is a parameter equal to 35%.
- *Grid carbon intensity BOS other* is the grid carbon intensity of the country where BOS components different than the inverter are manufactured [gCO$_{2\text{-eq}}$/kWh]. The country-specific grid carbon intensities applied in the model are obtained from the most recent database published on the website Our world in data (179), providing values for the year 2021. It is observed that the database is compiled with data from Ember and BP publications (179).
- *Grid carbon intensity inverter* is the grid carbon intensity of the country where the inverter is manufactured in gCO$_{2\text{-eq}}$/kWh.

The $CO_{2\text{-eq}}$ emission intensity of the BOS manufacturing phase is computed as per the following equation:

$$CO_{2-eq}\ Emission\ intensity\ BOS\ manufacturing\left[\frac{gCO_{2-eq}}{kWh}\right] = \frac{CO_{2-eq}\ Emissions\ BOS\ manufacturing[gCO_{2-eq}]}{Electricity\ produced\ during\ lifetime[kWh]}$$

Where:

- $CO_{2\text{-}eq}$ *Emissions BOS manufacturing* represents the $CO_{2\text{-eq}}$ emissions released during the BOS manufacturing phase, computed according to Equation 5.
- *Electricity produced during lifetime* represents the electricity produced [kWh] over the lifetime of the PV system computed by Equation 1.

4.5. Transportation

The transportation phase is defined in the evaluation framework as the delivery of PV modules and BOS components from the respective factory of manufacturing to the installation location. The manufacturing location can be different between PV modules and BOS components: Mukisa et al. (105) mention that in most cases the different components of a PV system are imported from different countries. As observed in Paragraph 2.2.5.4, the most common transport modes for PV modules and BOS components are represented by ships over water and trucks over land: the same approach is adopted in the model. In line with the methodology from Mukisa et al. (105) presented in the literature review chapter, the modeling technique adopted consider the distance covered, the mass transported, and the specific energy consumption of the modes of transport employed. Thus, the first step consists in defining the weight of modules. As mentioned in Section 4.3, not all modules technologies are framed in the evaluation framework. Monocrystalline, multicrystalline, CIS, and a-Si modules are framed, while the remaining technologies are frameless in the model. The weights of monocrystalline, multicrystalline, and CIS modules inclusive of the aluminum frame are computed from data in the IEA LCI Report 2020 and are equal to 13.12 kg/m^2, 13.23 kg/m^2, and 17.10 kg/m^2, respectively (171). The weight of framed a-Si modules is found in the LCI Report from ESU-services and it is equal to 8.20 kg/m^2 in the model (168). The weight of frameless CdTe modules applied in the model is 16.00 kg/m^2 according to the IEA LCI Report 2020 (171). The weight of unframed OPV modules is found in the paper from Serrano-Lujan et al. (102) and it is equal to 0.30 kg/m^2. Table 7 provides a summary of the specific modules' weights applied in the evaluation framework for the different technologies.

Technology	Specific modules weight [kg/m^2]
Monocrystalline	13.12
Multicrystalline	13.23
CdTe	16.00
CIS	17.10
a-Si	8.20
OPV	0.30

Table 7: Specific modules weight of the PV technologies considered (Own production).

The specific energy consumptions of the transport modes employed are now defined. For road freight transportation, the value of the specific primary energy consumption applied in the model is equal to 1.21 MJ/(ton*km), according to data from Deutsche Bahn AG, one of the world's leading logistics companies (182) (183). It is observed that value applied in the model is consistent with data from selected contributions from the literature, such as Andrés and Padilla (184). The specific primary energy consumption of maritime freight transportation applied in the model is equal to 0.09 MJ/(ton*km), according to data from Deutsche Banh AG (182). The parameter applied is consistent with values from the IEA (185). The impact in terms of cumulative energy demand of the modules transportation is computed thanks to Equation 6.

Equation 6

$$\begin{aligned} CED\ Modules\ Transportation[MJ] \\ = Specific\ weight\left[\frac{kg}{m^2}\right] * Area[m^2] * 0.001\left[\frac{ton}{kg}\right] \\ * \left(Road\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ modules\ road[km]\right. \\ \left. + Water\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ modules\ water[km]\right) \end{aligned}$$

Where:

- *Specific weight* indicates the weight of the modules per unit of area [kg/m^2]. The values applied in the model for the different technologies are provided in Table 7.

- *Area* indicates the area of modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.
- *Road CED* and *Water CED* indicate the specific primary energy consumptions of road and water transportation. In the model, they are equal to 1.21 MJ/(ton*km) and 0.09 MJ/(ton*km), respectively.
- *Distance modules road* and *Distance modules water* indicates the distances covered [km] by mode of transport in the modules transportation.

In order to evaluate the impact of modules transportation in terms of $CO_{2\text{-eq}}$ emissions, the specific emissions of the transport modes considered are needed. The specific emissions indicated in Table 8 are provided from the UK Government and are applied in the model (186).

Transport mode	Specific emissions [$gCO_{2\text{-eq}}$/(ton*km)]
Road	106.5
Maritime	13.2

Table 8: Specific emission factors for the transport modes considered (186).

It is observed that the values in Table 8 are consisted with selected contributions from the literature, such as Cristea et al. (187). The $CO_{2\text{-eq}}$ emissions from modules transportation are computed according to Equation 7.

Equation 7

$$\begin{aligned} &CO_{2-eq}\ Emissions\ Modules\ Transportation\left[gCO_{2-eq}\right] \\ &\quad = Specific\ weight\left[\frac{kg}{m^2}\right] * Area\left[m^2\right] * 0.001\left[\frac{ton}{kg}\right] \\ &\quad * \left(Road\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ modules\ road\left[km\right]\right. \\ &\quad \left. + Water\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ modules\ water\left[km\right]\right) \end{aligned}$$

Where:

- *Specific weight* indicates the weight of modules per unit of area [kg/m^2]. The values applied in the model for the different technologies are provided in Table 7.
- *Area* indicates the area of modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of

the system. The values of the specific areas [m²/kW] applied in the model are indicated in Table 5.

- *Road* $CO_{2\text{-}eq}$ and *Water* $CO_{2\text{-}eq}$ indicate the specific $CO_{2\text{-}eq}$ emissions of road and water transportation. In the model, they are equal to 106.5 $gCO_{2\text{-}eq}$/(ton*km) and 13.2 $gCO_{2\text{-}eq}$/(ton*km), respectively.
- *Distance modules road* and *Distance modules water* indicates the distances covered [km] by mode of transport in the modules transportation.

The next step to model the transportation phase consists in computing the impact of BOS components transportation. An approach similar to the one applied for modules is adopted. First, the weights of BOS components are defined. The weight of the inverter is gathered from the LCI report from ESU-services (168), and it is equal to 5.98 kg/kW in the model. It is observed that the value is close to other estimates found in the literature, such as 6.33 kg/kW computed from data in Akinyele (84), and 7.40 kg/kW calculated from data in Ng and Mithraratne (154). The weight of the mounting structure is found in the ESU-services' LCI Report, and it is equal to 10.37 kg/m² (168). The weight of the remaining BOS components, represented by cables and equipment for grid connection, is computed from data in the IEA LCI Report 2020 and it is equal to 2.75 kg/kW (171). In detail, the impact in terms of cumulative energy demand of the BOS transportation is computed thanks to Equation 8.

Equation 8:

$$\begin{aligned}
&CED\ BOS\ Transportation[MJ] \\
&\quad = \left(Specific\ weight\ BOS\ structural\left[\frac{kg}{m^2}\right] * Area[m^2]\right. \\
&\quad \left. + Specific\ weight\ BOS\ other\ electrical\left[\frac{kg}{kW}\right] * Capacity[kW]\right) \\
&\quad * 0.001\left[\frac{ton}{kg}\right] \\
&\quad * \left(Road\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ BOS\ other\ road[km]\right. \\
&\quad \left. + Water\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ BOS\ other\ water[km]\right) \\
&\quad + Specific\ weight\ inverter\left[\frac{kg}{kW}\right] * Capacity[kW] * 0.001\left[\frac{ton}{kg}\right] \\
&\quad * \left(Road\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ inverter\ road[km]\right. \\
&\quad \left. + Water\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ inverter\ water[km]\right)
\end{aligned}$$

Where:

- *Specific weight BOS structural* indicates the weight of the mounting structure, equal to 10.37 kg/m^2.
- *Area* indicates the area of modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.
- *Specific weight BOS other electrical* indicates the weight of the electrical components different than the inverter, represented by cables and equipment for grid connection, and it is equal to 2.75 kg/kW.
- *Capacity* represents the power of the PV system in kW.
- *Specific weight inverter* indicates the weight of the inverter, and it is equal to 5.98 kg/kW.
- *Road CED* and *Water CED* indicate the specific primary energy consumptions of road and water transportation. In the model, they are equal to 1.21 MJ/(ton*km) and 0.09 MJ/(ton*km), respectively.
- *Distance BOS other road* and *Distance BOS other water* indicate the distances covered [km] by mode of transport in the transportation of BOS components different than the inverter.
- *Distance inverter road* and *Distance inverter water* indicate the distances covered [km] by mode of transport in the transportation of the inverter.

The $CO_{2\text{-eq}}$ emissions from BOS transportation are computed as per Equation 9.

Equation 9

$$
\begin{aligned}
&CO_{2-eq}\ Emissions\ BOS\ Transportation\left[gCO_{2-eq}\right]\\
&\quad = \left(Specific\ weight\ BOS\ structural\left[\frac{kg}{m^2}\right] * Area[m^2]\right.\\
&\quad \left. + Specific\ weight\ BOS\ other\ electrical\left[\frac{kg}{kW}\right] * Capacity[kW]\right)\\
&\quad * 0.001\left[\frac{ton}{kg}\right]\\
&\quad * \left(Road\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ BOS\ other\ road[km]\right.\\
&\quad \left. + Water\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ BOS\ other\ water[km]\right)\\
&\quad + Specific\ weight\ inverter\left[\frac{kg}{kW}\right] * Capacity[kW] * 0.001\left[\frac{ton}{kg}\right]\\
&\quad * \left(Road\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ inverter\ road[km]\right.\\
&\quad \left. + Water\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ inverter\ water[km]\right)
\end{aligned}
$$

Where:

- *Specific weight BOS structural* indicates the weight of the mounting structure, equal to 10.37 kg/m^2.
- *Area* indicates the area of modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.
- *Specific weight BOS other electrical* indicates the weight of the electrical components different than the inverter, represented by cables and equipment for grid connection, and it is equal to 2.75 kg/kW.
- *Capacity* represents the power of the PV system in kW.
- *Specific weight inverter* indicates the weight of the inverter, and it is equal to 5.98 kg/kW.
- *Road* $CO_{2\text{-}eq}$ and *Water* $CO_{2\text{-}eq}$ indicate the specific $CO_{2\text{-eq}}$ emissions of road and water transportation. In the model, they are equal to 106.5 g$CO_{2\text{-eq}}$/(ton*km) and 13.2 g$CO_{2\text{-eq}}$/(ton*km), respectively.
- *Distance BOS other road* and *Distance BOS other water* indicate the distances covered [km] by mode of transport in the transportation of BOS components different than the inverter.
- *Distance inverter road* and *Distance inverter water* indicate the distances covered [km] by mode of transport in the transportation of the inverter.

Finally, the cumulative energy demand and the $CO_{2\text{-eq}}$ emissions from the transportation phase are computed by summing the contributions from modules and BOS transportation, according to Equation 10 and Equation 11.

Equation 10

$$\begin{aligned}E_{Transportation}[MJ]\\ &= CED\ Modules\ Transportation[MJ]\\ &+ CED\ BOS\ Transportation[MJ]\end{aligned}$$

Where:

- *CED Modules Transportation* is the cumulative energy demand [MJ] of the modules transportation. It is computed by Equation 6.
- *CED BOS Transportation* is the cumulative energy demand [MJ] of the BOS transportation. It is computed by Equation 8.

Equation 11

$$\begin{aligned}CO_{2-eq}\ Emissions\ Transportation\left[gCO_{2-eq}\right]\\ &= CO_{2-eq}\ Emissions\ Modules\ Transportation\left[gCO_{2-eq}\right]\\ &+ CO_{2-eq}\ Emissions\ BOS\ Transportation[gCO_{2-eq}]\end{aligned}$$

Where:

- $CO_{2\text{-}eq}$ *Emissions Modules Transportation* are the $CO_{2\text{-}eq}$ emissions released from modules transportation. They are computed by Equation 7.
- $CO_{2\text{-}eq}$ *Emissions BOS Transportation* are the $CO_{2\text{-}eq}$ emissions released from BOS transportation. They are computed by Equation 9.

Finally, the $CO_{2\text{-}eq}$ emission intensity of the transportation phase is obtained by the ratio of the $CO_{2\text{-}eq}$ emissions computed by Equation 11 to the energy produced by the PV system during its lifetime, computed by Equation 1:

$$CO_{2-eq}\ Emission\ intensity\ Transportation\left[\frac{gCO_{2-eq}}{kWh}\right] = \frac{CO_{2-eq}\ Emissions\ Transportation[gCO_{2-eq}]}{Electricity\ produced\ during\ lifetime[kWh]}$$

4.6. Installation

The installation phase is defined in the evaluation framework as the integration of modules and BOS components and the connection to the grid (90). Following an approach similar to the one found in Jia et al. (143), the phase is modeled considering an electricity consumption of 10 kWh/kW to install the system. The parameter in kWh/kW is converted into kWh/m^2: the latter unit is needed since different PV technologies have different specific areas in m^2/kW. By considering the values of the area [m^2] and of the power [W] indicated by the authors (143), the electricity consumption of 10 kWh/kW is equivalent to 1.68 kWh/m^2. The value obtained is then converted into the equivalent primary energy by dividing with the model-specific grid conversion efficiency of 0.35, and further converted in MJ. Consequently, the parameter applied in the evaluation framework for the specific primary energy consumption of the installation phase is equal to 17.28 MJ/m^2. The cumulative energy demand of the installation phase is computed according to Equation 12.

Equation 12:

$$E_{Installation}[MJ] = Specific\ CED\ Installation\left[\frac{MJ}{m^2}\right] * Area[m^2]$$

Where:

- *Specific CED Installation* is the specific primary energy consumption of the installation phase. In the model, it is equal to 17.28 MJ/m^2.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of

the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.

As mentioned, the modeling approach adopted considers the energy consumption during the installation phase to be composed of electricity (143). Thus, $CO_{2\text{-}eq}$ emissions of the installation phase are computed starting from the cumulative energy demand, considering the grid carbon intensity and the grid conversion efficiency, according to Equation 13.

Equation 13:

$$\begin{aligned} CO_{2-eq}\ Emissions\ Installation\left[gCO_{2-eq}\right] \\ = E_{Installation}[MJ] * Grid\ conversion\ efficiency[\%] \\ * Grid\ carbon\ intensity\ installation\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right] \end{aligned}$$

Where:

- $E_{Installation}$ is the cumulative energy demand of the installation phase in MJ. It is computed according to Equation 12.
- *Grid conversion efficiency* represents the conversion efficiency of the grid from primary energy to electricity. In the model, it is a parameter equal to 35%.
- *Grid carbon intensity installation* is the grid carbon intensity of the country where the PV system is installed [$gCO_{2\text{-}eq}$/kWh]. The country-specific grid carbon intensities applied in the model are obtained from the most recent database published on the website Our world in data (179), providing values for the year 2021. It is observed that the database is compiled with data from Ember and BP publications (179).

The $CO_{2\text{-}eq}$ emission intensity of the installation phase is computed by dividing the $CO_{2\text{-}eq}$ emissions released by the lifetime energy production, as per the following formula:

$$\begin{aligned} CO_{2-eq}\ Emission\ intensity\ Installation\left[\frac{gCO_{2-eq}}{kWh}\right] \\ = \frac{CO_{2-eq}\ Emissions\ Installation\left[gCO_{2-eq}\right]}{Electricity\ produced\ during\ lifetime[kWh]} \end{aligned}$$

Where:

- *$CO_{2\text{-}eq}$ Emissions Installation* represents the $CO_{2\text{-}eq}$ emissions of the installation phase computed by Equation 13.
- *Electricity produced over lifetime* is the electricity generated [kWh] over the lifetime of the system computed by Equation 1.

4.7. Use

The use phase is defined in the model as encompassing the maintenance activities, as well as the manufacturing of the spare inverter and its transportation from the manufacturing location to the installation site. Considering the maintenance activities, the value of the primary energy consumption applied in the model is gathered from Mason et al. (181). The value indicated by the mentioned scholars is equal to 45 MJ/m^2 for a 30-year lifetime, and it includes the energy consumption of vehicles for maintenance activities as well as the energy consumption of the office for the PV plant staff (181). In order to take into account the different lifetimes of the PV technologies considered in the model, the mentioned value is converted into the equivalent yearly primary energy consumption, by dividing the consumption of 45 MJ/m^2 by the lifetime of 30 years. Consequently, the primary energy consumption of the maintenance activities applied in the evaluation framework is equal to 1.5 MJ/(m^2*year). The value applied in the model is the same for all the PV technologies considered. This is justified by looking at data from the Product Environmental Footprint (PEF) report on electricity from photovoltaic commissioned by the European Commission in the context of the PEF pilots (188). The report evaluates monocrystalline, multicrystalline, micromorphous silicon, CIS, and CdTe technologies, and suggests that the maintenance activities across the different technologies do not differ, since they are modeled with the specific consumption of 20 l/m^2 of water for cleaning.

Considering the replacement of the inverter, it is modeled in the evaluation framework assuming the lifetime of the inverter as equal to 15 years (37). As mentioned, the manufacturing of the spare inverter and its transportation from the manufacturing location to the installation site are included in the use phase. The primary energy consumption in the inverter manufacturing process is modeled following the approach presented in Section 4.4 covering the BOS manufacturing phase. Similarly, the cumulative energy demand during the transportation of the inverter is modeled according to the same methodology presented in Section 4.5 covering the transportation phase. In detail, the cumulative energy demand of the use phase is computed as per Equation 14.

Equation 14:

$$
\begin{aligned}
E_{Use}[MJ] = {} & Specific\ CED\ maintenance \left[\frac{MJ}{Year * m^2}\right] * Area[m^2] * Lifetime[Year] \\
& + \left(CEILING\left(\frac{Lifetime[Year]}{Inverter\ lifetime[Year]}\right) - 1\right) \\
& * (Specific\ CED\ inverter \left[\frac{MJ}{kW}\right] * Capacity[kW] \\
& + (Specific\ weight\ inverter \left[\frac{kg}{kW}\right] * Capacity[kW] * 0.001 \left[\frac{ton}{kg}\right]) \\
& * (Road\ CED \left[\frac{MJ}{ton * km}\right] * Distance\ inverter\ road[km] \\
& + Water\ CED \left[\frac{MJ}{ton * km}\right] * Distance\ inverter\ water[km]))
\end{aligned}
$$

Where:

- *Specific CED maintenance* is the primary energy demand during the maintenance activities. It is equal to 1.5 MJ/(m^2*year) in the model.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.
- *Lifetime* indicates the lifetime of the PV system in years. It depends on the PV technology considered. The values of the lifetime applied in the model are indicated in Table 5.
- *CEILING* indicates the Excel function rounding up a given number to the nearest integer.
- *Inverter lifetime* is the lifetime of the inverter, and it is equal to 15 years in the model.
- *Specific CED inverter* is the cumulative energy demand to manufacture the inverter, and it is equal to 1321 MJ/kW in the model.
- *Specific weight inverter* indicates the weight of the inverter. It is equal to 5.98 kg/kW in the model.
- *Capacity* is the power of the PV system in kW.
- *Road CED* and *Water CED* indicate the specific primary energy consumption of road and water transportation. In the model, they are equal to 1.21 MJ/(ton*km) and 0.09 MJ/(ton*km), respectively.
- *Distance inverter Road* and *Distance inverter water* are the distances covered [km] by road and water to transport the inverter from the manufacturing factory to the installation location.

As mentioned, the values of the primary energy demand of the maintenance activities applied in the evaluation framework includes the energy consumption of vehicles for maintenance activities as well as the energy consumption of the office for the PV plant staff (181). Data from Nordin et al. (83) as well as from Sinha and de Wild-Scholten (189) suggest that electricity can represent an important component of the energy consumption during maintenance activities. Thus, $CO_{2\text{-eq}}$ emissions due to maintenance activities are computed starting from the primary energy consumption, considering the grid carbon intensity and the conversion of primary energy into electricity. The computation of the $CO_{2\text{-eq}}$ emissions arising from inverter manufacturing and transportation follows the same approach presented in the BOS manufacturing and transportation phases, respectively. In detail, the $CO_{2\text{-eq}}$ emissions from the use phase are computed according to Equation 15.

Equation 15:

$$\begin{aligned}
&CO_{2-eq}\ Emissions\ Use\left[gCO_{2-eq}\right]\\
&\quad = Specific\ CED\ maintenance\left[\frac{MJ}{Year * m^2}\right] * Area\left[m^2\right]\\
&\quad * Lifetime[Year] * Grid\ conversion\ efficiency[\%]\\
&\quad * Grid\ carbon\ intensity\ installation\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right]\\
&\quad + \left(CEILING\left(\frac{Lifetime[Year]}{Inverter\ lifetime[Year]}\right) - 1\right)\\
&\quad * (Specific\ CED\ inverter\left[\frac{MJ}{kW}\right] * Capacity[kW]\\
&\quad * Grid\ conversion\ efficiency[\%]\\
&\quad * Grid\ carbon\ intensity\ inverter\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right]\\
&\quad + \left(Specific\ weight\ inverter\left[\frac{kg}{kW}\right] * Capacity[kW] * 0.001\left[\frac{ton}{kg}\right]\right)\\
&\quad * \left(Road\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ inverter\ road[km]\right.\\
&\quad \left. + Water\ CO_{2-eq}\left[\frac{gCO_{2-eq}}{ton * km}\right] * Distance\ inverter\ water[km]\right))
\end{aligned}$$

Where:

- *Specific CED maintenance* is the primary energy demand during the maintenance activities. It is equal to 1.5 MJ/(m^{2}*year) in the model.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m^2/kW] applied in the model are indicated in Table 5.

- *Lifetime* indicates the lifetime of the PV system. It depends on the PV technology considered. The values of the lifetime applied in the model are indicated in Table 5.
- *Grid conversion efficiency* is a parameter equal to 35% indicating the grid conversion efficiency from primary energy to electricity.
- *Grid carbon intensity installation* is the grid carbon intensity of the grid where the PV system is installed [gCO_{2-eq}/kWh]. The country-specific grid carbon intensities applied in the model are obtained from the most recent database published on the website Our world in data (179), providing values for the year 2021. It is observed that the database is compiled with data from Ember and BP publications (179).
- *Grid carbon intensity inverter* is the grid carbon intensity of the grid where the inverter is manufactured [gCO_{2-eq}/kWh]. In the model, the country-specific grid carbon intensities are obtained from the database published on the website Our World in data (179).
- *CEILING* indicates the Excel function rounding up a given number to the nearest integer.
- *Inverter lifetime* is the lifetime of the inverter, and it is equal to 15 years in the model.
- *Specific CED inverter* is the cumulative energy demand to manufacture the inverter, and it is equal to 1321 MJ/kW in the model.
- *Specific weight inverter* indicates the weight of the inverter. It is equal to 5.98 kg/kW in the model.
- *Capacity* is the power of the PV system.
- *Road CO_{2-eq} and Water CO_{2-eq}* represent the specific CO_{2-eq} emissions of road and water transportation. In the model, they are equal to 106.5 gCO_{2-eq}/(ton*km) and 13.2 gCO_{2-eq}/(ton*km), respectively.
- *Distance inverter Road* and *Distance inverter water* are the distances covered [km] by road and water to transport the inverter from the manufacturing factory to the installation location.

The CO_{2-eq} emission intensity of the use phase is computed as the ratio of the CO_{2-eq} emissions released to the electricity produced over the lifetime of the PV system, as follows:

$$CO_{2-eq}\ Emission\ intensity\ Use \left[\frac{gCO_{2-eq}}{kWh}\right] = \frac{CO_{2-eq}\ Emissions\ Use\left[gCO_{2-eq}\right]}{Electricity\ produced\ during\ lifetime[kWh]}$$

Where:

- *$CO_{2\text{-}eq}$ emissions Use* represents the $CO_{2\text{-eq}}$ emissions released during the use phase computed by Equation 15.
- *Electricity produced during lifetime* indicates the electricity produced [kWh] over the lifetime of the system computed by Equation 1.

4.8. End-of-life

The end-of-life phase is defined in the evaluation framework as the process of deconstruction of the PV plant and recycling of components (132). The end-of-life stage holds a fundamental importance in the future long-term sustainability of PV technologies (98). PV modules' end-of-life in EU member states is regulated by the Directive on Waste Electrical and Electronic Equipment (WEEE) (190). The directive states that the recovery rate by mass shall be 85% and the recycling rate 80% (188) (190). Furthermore, it is observed that a significant research effort is undergoing to improve recycling methods (191). For example, the Full Recycling EoL Procedure (FRELP) is a process developed from EU research to meet the targets of the directive (77). It consists into a combination of chemical and mechanical processes (77). Concerning the modeling approach applied in the model, it is decided in line with the importance of the end-of-life stage and the recycling for the future sustainability of PV energy, to consider, when data are available, the recycling of PV systems in accordance with the WEEE directive (188).

The modeling approach adopted, similarly to the one encountered in Lima et al. (61), starts from a specific value of the primary energy demand [MJ/m^2] in the recycling process. Considering the monocrystalline PV technology, Latunussa et al. (57) indicate the value of 3.15 MJ/kg for the cumulative energy demand of the FRELP procedure applied to crystalline silicon PV modules waste. By considering the mass [kg] and the area [m^2] of modules provided by the scholars, the mentioned value is equivalent to 43 MJ/m^2 (57). It is observed that Latunussa et al. (57) do not consider the recycling of BOS components. Thus, data to model the end-of-life phase are gathered from the Product Environmental Footprint (PEF) report on electricity from photovoltaic commissioned by the European Commission in the context of PEF pilots, where the EoL of monocrystalline PV systems inclusive of BOS components (except the inverter) is modeled according to targets of the WEEE directive (188). As mentioned, the inverter is excluded from the boundaries considered in the PEF report. Nevertheless, the document is considered as the source of data since it represents one of the few contributions proposing a modeling of the end-of-life consistent with the WEEE directive. Given the limited data available, the PEF report considers for the monocrystalline technology the same data adopted to model the recycling of the CdTe technology, scaling them by a factor of 1.5 (188). The cumulative energy demand of 96.26 MJ/m^2 during the end-of-life phase is applied in the model by considering the specific cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the PEF report (188). It is observed that the value is higher than the abovementioned one from Latunussa et al. (57) equal to 43 MJ/m^2: this is reasonable since the PEF report also considers the recycling of BOS components in addition to the recycling of PV modules.

Concerning the multicrystalline technology, the same PEF report is applied as the source of data (188). Given the limited data available, the report considers for the multicrystalline technology the same data adopted to model the recycling of the CdTe technology, scaling them by a factor of 1.5 (188). The value of 91.72 MJ/m^2 for the cumulative energy demand during the end-of-life phase is applied in the model by considering the specific cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the report (188). It is observed that the value is higher than the abovementioned one from Latunussa et al. (57) equal to 43 MJ/m^2 to recycle crystalline silicon PV modules waste, but this is considered reasonable given that the latter scholars do not consider the recycling of BOS components.

Considering the EoL of CdTe technology, Held and Ilg (62) indicate the value of 81 MJ/m^2 for the primary energy consumption during the recycling process. Considering the specific cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the PEF report, it is applied in the model the value of 92.49 MJ/m^2 for the cumulative energy demand in the end-of-life phase of CdTe modules and BOS components (188). It is observed that the value is close to the abovementioned one computed by Held and Ilg (62). This is considered reasonable since both contributions refer to First Solar's CdTe modules recycling procedure.

Large scale CIS recycling projects are not commercialized yet (188). Consequently, a lack of data is observed. The solution applied in the PEF report consists in modeling the recycling of CIS PV systems by adopting the same data applied to model the recycling of CdTe PV systems and scaling them by a factor of 1.5. Considering the specific cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the cited report, the value applied in the model is equal to 121.96 MJ/m^2 for the cumulative energy demand of the EoL phase of CIS PV systems inclusive of BOS components (188).

Given the absence of data, the end-of-life of micromorphous silicon PV systems is modeled in the PEF report similarly to CdTe ones, adapting the data applied for CdTe by a factor of 1.5 (188). A micromorphous silicon cell is made by an amorphous silicon top cell and a microcrystalline silicon bottom cell (192) (193) (194) (195). Given the limited data available, it is decided to apply the data indicated in the PEF report for the micromorphous technology to model the end-of-life of amorphous silicon PV systems. Considering the specific cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the report, the value of 113.62 MJ/m^2 for the cumulative energy demand of the end-of-life phase of a-Si PV systems comprehensive of BOS components is applied in the model (188).

It is observed that limited information is available in the literature concerning the recycling of OPV modules (173). This can be justified by the fact that OPV technology is not commercialized yet. The end-of-life of OPV technology is modeled in the evaluation framework considering the separation of modules from the mounting structure, the transportation of components to a processing facility, and a recycling process to recover valuable materials. As suggested by Jia et al. (143), an electricity consumption of 0.1 kWh/kW is needed to separate modules from the mounting structure. Considering the specific area of 5.95 m^2/kW indicated by the mentioned scholars (143), and the model-specific grid conversion efficiency from primary energy to electricity of 35%, the electricity consumption is equivalent to 0.17 MJ/m^2 of primary energy demand. Furthermore, transportation to the processing facility is completed by truck and a distance of 300 km is assumed. The distance chosen is in line with what indicated in Latunussa et al. (57) (300 to 500 km), and of the same order of magnitude of what found in Lim et al. (196) (100 km) to transport components from the installation location to the end-of-life site. As for the process to recover valuable materials, Sondegaard et al. (197) analyze a recycling procedure to recover silver from OPV modules, since it represents an important component of the electrodes. The mentioned scholars provide the value of 0.08 MJ/m^2 for the primary energy consumption of the recycling process. To sum up, the modeled scenario for OPV technology include the primary energy consumption to separate modules from the mounting structure and recover silver, equal to 0.25 MJ/m^2, as well as the transportation to the processing site covering a distance of 300 km.

In Paragraph 2.2.5.7, it was observed that multiple scholars consider the benefits arising from the end-of-life phase. It is decided to include the assessment of benefits from the end-of-life phase in the evaluation framework, so that two options for the end-of-life phase can be considered: with benefits and without benefits. An approach similar to the one from Latunussa et al. (57) is adopted, namely considering benefits from the end-of-life phase as a credit reducing the cumulative energy demand of the PV system over its life cycle. Starting from the monocrystalline technology, data are gathered from the PEF report on electricity from photovoltaic commissioned by the European Commission in the context of PEF pilots, where the end-of-life of monocrystalline PV system inclusive of BOS components (except inverter) is modeled according to targets of the WEEE directive (188). The report considers credits from recycling materials such as glass, aluminum, and steel. In particular, the mentioned contribution assumes an efficiency of glass recycling equal to 90%, while the recycling efficiency of aluminum and steel from the mounting structure as well as of copper and steel from the electric installations is equal to 100% (188). It is observed that in the PEF report 50% of the recycling benefits are allocated to the PV system under analysis, and 50% to the system reusing the product in the future, according to the 50:50 approach (188) (198). It emerges from the literature that the 50:50 approach is not frequently used by scholars in LCA (199). Thus, it is considered in the evaluation framework to allocate 100% of the benefits to the PV system under analysis, according to the avoided burden approach (188) (198). The avoided burden approach is the most used in the literature (200), and the preferred allocation method in multiple industries, such as the metal and the mining ones (201). According to the avoided burden approach, recycled materials replace the competing primary raw materials, so that the environmental burdens from the replaced primary materials are subtracted from the system (202). Considering the specific benefits in terms of cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the PEF report, the value of -685.72 MJ/m^2 for the benefits in terms of cumulative energy demand of the end-of-life phase of monocrystalline PV systems is applied in the model (188).

Considering multicrystalline PV systems, the value of -685.22 MJ/m^2 for the benefits of the end-of-life phase in terms of cumulative energy demand is applied in the model considering the specific benefits in terms of cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the PEF report (188).

Considering CdTe PV systems, from the results reported by Held and Ilg (62) it is computed the value of -93.52 MJ/m^2 for the primary energy benefits of the end-of-life phase. The estimate is compared to the value of -622.04 MJ/m^2 computed from the PEF report taking into account the specific benefits in terms of cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated (188). It is observed that the value obtained from the PEF report is one order of magnitude bigger than the above mentioned one computed from results by Held and Ilg (62). It is observed that the latter scholars only examine modules, cables, and junction boxes recycling, while in the PEF report it is considered the recycling of more BOS components. The value applied in the model is then equal to -622.04 MJ/m^2.

Considering the CIS technology, the value of -704.96 MJ/m^2 for the benefits in terms of cumulative energy demand from the end-of-life phase of CIS PV systems inclusive of the BOS is applied in the model considering the specific benefits in terms of cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the PEF report (188).

As mentioned when modeling the scenario without benefits, given the limited data available, the end-of-life of a-Si PV systems is modeled in the evaluation framework considering data from the PEF report. The value of -723.08 MJ/m^2 for the benefits in terms of cumulative energy demand from the end-of-life phase is applied in the model taking into account the specific benefits in terms of cumulative energy demand [MJ/kWh], the energy produced [kWh], and the area [m^2] indicated in the PEF report (188).

It is observed that a limited number of contributions assess the credits from the EoL phase of OPV systems. Tsang et al. (170) consider the incineration of OPV modules, resulting in 4.95 MJ of electricity per kg of modules incinerated. Taking into account the specific weight [m^2/kg] indicated by the mentioned scholars, and the model-specific conversion efficiency from primary energy to electricity equal to 35%, the 4.95 MJ of electricity are equivalent to -3.11 MJ/m^2 of credits in terms of primary energy. Sondergaard et al. (197) examine the recovery of silver from OPV modules with a 72% efficiency. The credits in terms of primary energy demand are computed as equal to -4.99 MJ/m^2 according to data in the cited contribution (197).

To sum up, the modeled scenario for OPV technology includes both the credits from incineration (-3.11 MJ/m^2) and from silver recycling (-4.99 MJ/m^2), so that the total benefits of the end-of-life phase in terms of cumulative energy demand are equal to -8.10 MJ/m^2.

Table 9 provides a recapitulation of the values applied in the evaluation framework for the cumulative energy demand of the end-of-life phase of the six PV technologies considered. The first column, Specific CED EoL, indicates the value of the cumulative energy demand of the EoL process, without considering the benefits. The second column, Specific CED EoL benefits, indicates the values of the benefits in terms of cumulative energy demand arising from the EoL phase. The third column, Specific CED EoL benefits included, is obtained as the sum of the first two columns and represents the value of the cumulative energy demand of the EoL phase comprehensive of benefits.

Technology	Specific CED EoL [MJ/m²]	Specific CED EoL benefits [MJ/m²]	Specific CED EoL benefits included [MJ/m²]
Monocrystalline	96.26	-685.72	-589.46
Multicrystalline	91.72	-685.22	-593.50
CdTe	92.49	-622.04	-529.55
CIS	121.96	-704.96	-583.00
a-Si	113.62	-723.08	-609.46
OPV	0.25	-8.10	-7.85

Table 9: Values applied in the evaluation framework for the cumulative energy demand of the end-of-life phase (Own production).

For first- and second-generation technologies, the cumulative energy demand of the end-of-life phase is computed according to Equation 16.

Equation 16:

$$E_{End-of-life}[MJ] = Specific\ CED\ EoL\left[\frac{MJ}{m^2}\right] * Area[m^2]$$

Where:

- *Specific CED EoL* indicates the cumulative energy demand per unit of area of the end-of-life phase [MJ/m²]. The values of the cumulative energy demand per unit of area applied in the model for the different PV technologies are indicated in Table 9.
- *Area* is the surface of PV modules in m². It is equal to the product of the specific area [m²/kW] of the technology considered and the capacity [kW] of the system. The values of the specific areas [m²/kW] applied in the model are indicated in Table 5.

If the benefits from the EoL phase are considered, Equation 16 is modified by considering the parameter *Specific CED EoL benefits included* instead of *Specific CED EoL*, indicated in Table 9.

For OPV technology, the cumulative energy demand of the end-of-life phase is computed as per Equation 17.

Equation 17:

$$E_{End-of-life}[MJ] = Specific\ CED\ EoL\left[\frac{MJ}{m^2}\right] * Area[m^2] + Total\ system\ weight[ton] * Road\ CED\left[\frac{MJ}{ton * km}\right] * Distance\ EoL\ road[km]$$

Where:

- *Specific CED EoL* is the cumulative energy demand per unit of area to separate modules from the mounting structure and recover silver. It is equal to 0.25 MJ/m^2 in the model.
- *Area* is the surface of PV modules. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The value of the specific area of OPV modules applied in the model is 20 m^2/kW.
- *Total system weight* is the total weight of the system in ton. It is computed according to Equation 18.
- *Road CED* is specific primary energy consumption of road transportation. In the model it is equal to 1.21 MJ/(ton*km).
- *Distance EoL road* is the distance from the installation location to the processing facility. It is equal to 300 km in the model.

If the benefits from the EoL phase are considered, Equation 17 is modified by considering the parameter *Specific CED EoL benefits included* instead of *Specific CED EoL,* as indicated in Table 9. The total system weight is computed according to Equation 18.

Equation 18

$$Total\ system\ weight[ton] = \left(Specific\ weight\left[\frac{kg}{m^2}\right] * Area[m^2] + Weight\ electrical\ component\left[\frac{kg}{kW}\right] * Capacity[kW] + Specific\ weight\ BOS\ structural\left[\frac{kg}{m^2}\right] * Area[m^2]\right) * 0.001\left[\frac{ton}{kg}\right]$$

Where:

- *Specific weight* is the weight of modules per unit of area. For OPV modules, it is equal to 0.30 kg/m^2 in the model.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of

the system. The value of the specific area of OPV modules applied in the model is 20 m²/kW.

- *Weight electrical component* is the sum of the weight of the inverter, equal to 5.98 kg/kW, and the weight of the other electrical components, namely cables and equipment for grid connection, equal to 2.75 kg/kW. Consequently, it is equal to 8.73 kg/kW in the model.
- *Capacity* is the power of the PV system in kW.
- *Specific weight BOS structural* indicates the weight of the mounting structure. It is equal to 10.37 kg/m² in the model.

Latunussa et al. (57) indicate that electricity is used as an input for multiple processes in the recycling of first-generation PV systems. Examples of processes consuming electricity are the disassembly, the glass separation, and the modules cutting (57). Considering the recycling of CdTe PV systems, results from Held and Ilg (62) indicate that the main environmental impact, for example in terms of global warming potential, of the EoL phase is due to electricity consumption. As for the OPV technology, the scenario modeled in the evaluation framework considers the consumption of 0.1 kWh/kW of electricity to separate modules from the mounting structure (143), so that electricity is the main contributor to the primary energy demand of 0.25 MJ/m² to separate modules from the mounting structure and recover silver applied in the model. Given the three considerations above, it is decided to estimate the $CO_{2\text{-eq}}$ emissions released from the EoL phase starting from the cumulative energy demand, considering the grid carbon intensity of the country where the end-of-life phase takes place, and the grid conversion efficiency from primary energy to electricity. In the evaluation framework, the country where the end-of-life phase occurs corresponds with the country where the PV system is installed. Herceg et al. (99) observe that trade of PV waste between countries will likely arise in the future. It is left as a future improvement of the current evaluation framework the inclusion of scenarios considering the trade of PV waste across geographies. $CO_{2\text{-eq}}$ emissions from the end-of-life phase are computed according to the Equation 19 for first- and second-generation PV technologies.

Equation 19:

$$\begin{aligned} CO_{2-eq}\ Emissions\ End\text{-}of\text{-}life\left[gCO_{2-eq}\right] &= E_{End-of-life}[MJ] * Grid\ conversion\ efficiency[\%] \\ &* Grid\ carbon\ intensity\ installation\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right] \end{aligned}$$

Where:

- $E_{End\text{-}of\text{-}life}$ indicates the cumulative energy demand in MJ of the end-of-life phase computed from Equation 16.

- *Grid conversion efficiency* is a parameter indicating the grid conversion efficiency from primary energy to electricity. It is equal to 35% in the model.
- *Grid carbon intensity installation* indicates the grid carbon intensity of the country where the PV system is installed [gCO$_{2\text{-eq}}$/kWh]. The country-specific grid carbon intensities applied in the model are obtained from the most recent database published on the website Our world in data (179), providing values for the year 2021. It is observed that the database is compiled with data from Ember and BP publications (179).

Considering the OPV technology, Equation 20 is applied to compute the CO$_{2\text{-eq}}$ emissions of the end-of-life phase.

Equation 20:

$$\begin{aligned} &CO_{2-eq}\ Emissions\ End\text{-}of\text{-}life\left[gCO_{2-eq}\right] \\ &\qquad = Specific\ CED\ EoL\left[\frac{MJ}{m^2}\right] * Area[m^2] \\ &\qquad * Grid\ conversion\ efficiency[\%] \\ &\qquad * Grid\ carbon\ intensity\ installation\left[\frac{gCO_{2-eq}}{kWh}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right] \\ &\qquad + Total\ system\ weight[ton] * Distance\ road[km] \\ &\qquad * Road\ CO_{2-eq}[\frac{gCO_{2-eq}}{ton * km}] \end{aligned}$$

Where:

- *Specific CED EoL* is the cumulative energy demand per unit of area to separate OPV modules from the mounting structure and recover silver. It is equal to 0.25 MJ/m^2 in the model.
- *Area* is the surface of PV modules in m^2. It is equal to the product of the specific area [m^2/kW] of the technology considered and the capacity [kW] of the system. The value of the specific area of OPV modules applied in the model is 20 m^2/kW.
- *Grid conversion efficiency* is a parameter indicating the grid conversion efficiency from primary energy to electricity. It is equal to 35% in the model.
- *Grid carbon intensity installation* is the grid carbon intensity of the country where the PV system is installed [gCO$_{2\text{-eq}}$/kWh]. In the model, the country-specific grid carbon intensities are obtained from the most recent database published on the website Our World in data (179), providing values for the year 2021.
- *Total system weight* is the total mass of the system in ton. It is computed according to Equation 18.
- *Distance road* is the distance from the installation location to the processing facility. It is equal to 300 km in the model.

- *Road $CO_{2\text{-}eq}$* indicates the specific $CO_{2\text{-}eq}$ emissions of road transportation. In the model, it is equal to 106.5 $gCO_{2\text{-}eq}$/(ton*km).

If the benefits from the EoL phase are considered, Equation 20 is modified by considering the parameter *Specific CED EoL benefits included* instead of *Specific CED EoL*, indicated in Table 9.

Finally, the $CO_{2\text{-}eq}$ emission intensity of the end-of-life phase is computed as the ratio of the $CO_{2\text{-}eq}$ emissions of the end-of-life phase to the electricity generated over the lifetime of the PV system, as follows:

$$CO_{2-eq}\ Emission\ intensity\ End\text{-}of\text{-}life\left[\frac{gCO_{2-eq}}{kWh}\right] = \frac{CO_{2-eq}\ Emissions\ End\text{-}of\text{-}life\left[gCO_{2-eq}\right]}{Electricity\ produced\ during\ lifetime[kWh]}$$

Where:

- *$CO_{2\text{-}eq}$ Emissions End-of-life* indicates the $CO_{2\text{-}eq}$ emissions from the end-of-life phase computed according to Equation 19, for first- and second-generation technologies, or to Equation 20 for OPV technology.
- *Electricity produced during lifetime* indicates the electricity produced [kWh] over the lifetime of the system computed by Equation 1.

4.9. Evaluation framework recap

The developed evaluation framework permits to evaluate the environmental impact from cradle-to-grave of ground-mounted PV systems. Six different PV technologies can be assessed. As a recap of the model, the input variables needed, and the impact indicators computed are now presented.

4.9.1. Input variables

13 input variables are required to run the evaluation framework. Table 10 shows the input variables and their units of measure.

Input variables	
Capacity of PV system	[MW]
Country of installation	[-]
Country of modules manufacturing	[-]
Typology of PV	[-]
Modules distance road	[km]
Modules distance water	[km]
Inverter country of manufacturing	[-]
Inverter distance road	[km]
Inverter distance water	[km]
BOS (except inverter) country of manufacturing	[-]
BOS (except inverter) distance road	[km]
BOS (except inverter) distance water	[km]
End-of-life benefits	[-]

Table 10: Input variables of the evaluation framework (Own production).

The details of the input variables are here provided:

- Capacity of PV system.

This input variable indicates the capacity of the PV system and it is expressed in MW.

- Country of installation.

This input variable indicates the country where the PV system is installed. The country of installation defines the value of the solar irradiation [kWh/(m^2*year)] over the lifetime of the PV system, as well as the carbon intensity [$gCO_{2\text{-}eq}$/kWh] of the grid to which the system is connected.

- Country of modules manufacturing.

This input variable indicates the country where the manufacturing of modules takes place. The country of modules manufacturing defines the carbon intensity [$gCO_{2\text{-}eq}$/kWh] of the grid employed in the production process of PV modules.

- Typology of PV.

This input variable defines the PV technology considered. Six different technologies can be assessed by the evaluation framework: monocrystalline, multicrystalline, a-Si, CIS, CdTe, OPV.

- Modules distance road.

This input variable indicates the distance in km covered by road between the factory of manufacturing of PV modules and the location of installation.

- Modules distance road.

This input variable indicates the distance in km covered by water between the factory of manufacturing of PV modules and the place of installation.

- Inverter country of manufacturing.

This input variable indicates the country where the inverter is manufactured. The country of inverter manufacturing defines the carbon intensity [gCO_{2-eq}/kWh] of the grid employed in the production process of the inverter.

- Inverter distance road.

The input variable defines the distance in km covered by road from the factory of manufacturing of the inverter to the place of installation.

- Inverter distance water.

The input variable defines the distance in km covered by water from the factory of manufacturing of the inverter to the place of installation.

- BOS (except inverter) country of manufacturing.

This input variable indicates the country where the BOS components different than the inverter are manufactured. Consequently, it defines the carbon intensity [gCO_{2-eq}/kWh] of the grid employed in the production process of BOS components different than the inverter.

- BOS (except inverter) distance road.

This input variable defines the distance in km covered by road from the location of manufacturing of BOS components different than the inverter to the place of installation.

- BOS (except inverter) distance water.

This input variable defines the distance in km covered by water from the location of manufacturing of BOS components different than the inverter to the place of installation.

- End-of-life benefits.

This input variable permits to select whether the benefits from the end-of-life phase are considered or not.

4.9.2. Impact indicators

Table 11 illustrates the impact indicators computed by the evaluation framework and their units of measure.

Impact indicators	
Cumulative energy demand	[MJ]
Global warming potential	[gCO$_{2\text{-eq}}$/kwh]
Energy payback Time	[Year]
CO$_2$ payback time	[Year]

Table 11: Impact indicators of the evaluation framework (Own production).

The details of the impact indicators are now provided.

- Cumulative energy demand (CED).

  The CED is a measure of the primary energy consumed over the lifecycle of the system (78). It is indicated in MJ. It is computed according to Equation 21.

  Equation 21:

$$
\begin{aligned}
CED[MJ] = E_{Modules\ manufacturing}[MJ] + E_{BOS\ manufacturing}[MJ] \\
+ E_{Transportation}[MJ] + E_{Installation}[MJ] + E_{Use}[MJ] \\
+ E_{End-of-life}[MJ]
\end{aligned}
$$

  Where:

  - $E_{Modules\ Manufacturing}$ indicates the cumulative energy demand of the modules manufacturing phase in MJ. It is computed according to Equation 2.
  - $E_{BOS\ manufacturing}$ indicates the cumulative energy demand of the BOS manufacturing phase in MJ. It is computed according to Equation 4.
  - $E_{Transportation}$ indicates the cumulative energy demand of the transportation phase in MJ. It is computed according to Equation 10.
  - $E_{Installation}$ indicates the cumulative energy demand of the installation phase in MJ. It is computed according to Equation 12.
  - E_{Use} indicates the cumulative energy demand of the use phase in MJ. It is computed according to Equation 14.
  - $E_{End-of-life}$ indicates the cumulative energy demand of the end-of-life phase in MJ. It is computed according to Equation 16 for first- and second-generation technologies, and according to Equation 17 for OPV technology.

- Global warming potential (GWP).

The GWP is a measure of the effect on global warming of a PV system over its lifecycle (60). It is measured in $gCO_{2\text{-eq}}/kWh$ and is computed according to Equation 22.

Equation 22:

$$GWP[\frac{gCO_{2-eq}}{kWh}] = \frac{CO_{2-eq}\ Emissions\ during\ lifetime[gCO_{2-eq}]}{Electricity\ produced\ during\ lifetime[kWh]}$$

The numerator is computed as the sum of the $CO_{2\text{-eq}}$ emissions over the six phases composing the life cycle, as per the following formula:

$$\begin{aligned} CO_{2-eq}\ Emissions\ during\ lifetime\left[gCO_{2-eq}\right] \\ = CO_{2-eq}\ Emissions\ Modules\ manufacturing\left[gCO_{2-eq}\right] \\ + CO_{2-eq}\ Emissions\ BOS\ manufacturing\left[gCO_{2-eq}\right] \\ + CO_{2-eq}\ Emissions\ Transportation\left[gCO_{2-eq}\right] \\ + CO_{2-eq}\ Emissions\ Installation\left[gCO_{2-eq}\right] \\ + CO_{2-eq}\ Emissions\ Use\left[gCO_{2-eq}\right] \\ + CO_{2-eq}\ Emissions\ End\text{-}of\text{-}life\left[gCO_{2-eq}\right] \end{aligned}$$

Where:

- $CO_{2\text{-}eq}$ *Emissions Modules manufacturing* indicates the $CO_{2\text{-eq}}$ emissions of the modules manufacturing phase. They are computed according to Equation 3.
- $CO_{2\text{-}eq}$ *Emissions BOS manufacturing* indicates the $CO_{2\text{-eq}}$ emissions of the BOS manufacturing phase. They are computed according to Equation 5.
- $CO_{2\text{-}eq}$ *Emissions Transportation* indicates the $CO_{2\text{-eq}}$ emissions of the transportation phase. They are computed according to Equation 11.
- $CO_{2\text{-}eq}$ *Emissions Installation* indicates the $CO_{2\text{-eq}}$ emissions of the installation phase. They are computed according to Equation 13.
- $CO_{2\text{-}eq}$ *Emissions Use* indicates the $CO_{2\text{-eq}}$ emissions of the use phase. They are computed according to Equation 15.
- $CO_{2\text{-}eq}$ *Emissions End-of-life* indicates the $CO_{2\text{-eq}}$ emissions of the end-of-life phase. They are computed according to Equation 19 for first- and second-generation technologies, and according to Equation 20 for OPV technology.

The denominator of the GWP indicated in Equation 22 represents the electricity produced [kWh] over the lifetime of the PV system according to Equation 1.

- Energy payback Time (EPBT).

The EPBT is a measure of the time needed for an energy system to generate the same amount of energy that was consumed in the full life cycle of the system (81) (80). It is measured in years and is computed according to the following equation (82):

$$EPBT[Year] = \frac{CED[MJ]}{\frac{E_{produced}[\frac{MJ}{Year}]}{Grid\ conversion\ efficiency[\%]}}$$

Where:

- CED is the cumulative energy demand [MJ] computed by Equation 21.
- $E_{produced}$ is the mean annual energy produced by the PV system [MJ/Year]. It is computed according to the following formula:

$$E_{Produced}\left[\frac{MJ}{Year}\right] = Electricity\ produced\ during\ lifetime[kWh] * 3.6\left[\frac{MJ}{kWh}\right] * \frac{1}{Lifetime[Year]}$$

  Where:

  - *Electricity produced during lifetime* indicates the electricity produced [kWh] over the lifetime of the system computed by Equation 1.
  - *Lifetime* indicates the years of lifetime of the PV system considered. The values of the lifetime applied in the model are indicated in Table 5.
- *Grid conversion efficiency* is a parameter indicating the grid conversion efficiency from primary energy to electricity. It is equal to 35% in the model.

- CO_2 payback time (CO_2PBT).

The CO_2PBT is a measure of the time needed to offset the $CO_{2\text{-eq}}$ emissions released over the life cycle of the system by the $CO_{2\text{-eq}}$ emissions reduction generated by the system itself (80) (83). It is measured in years and is computed as per the following equation (80) (83):

$$CO_2PBT[Year] = \frac{CO_{2-eq}\ Emissions\ during\ lifetime[gCO_{2-eq}]}{CO_{2-eq}\ Emissions\ avoided[\frac{gCO_{2-eq}}{Year}]}$$

Where:

- *$CO_{2\text{-}eq}$ Emissions during lifetime* indicates the $CO_{2\text{-}eq}$ emissions released during the life cycle in $gCO_{2\text{-}eq}$. It represents the numerator of the GWP as per Equation 22.
- *$CO_{2\text{-}eq}$ Emissions avoided* is equal to the yearly $CO_{2\text{-}eq}$ emissions avoided associated to the production of the same amount of electricity with the local electricity mix of the country of installation, according to the following formula (80) (83):

$$CO_{2-eq}\ Emissions\ avoided\left[\frac{gCO_{2-eq}}{Year}\right] = Grid\ carbon\ intensity\ installation\left[\frac{gCO_{2-eq}}{kWh}\right] * Electricity\ produced\ during\ lifetime[kWh] * \frac{1}{Lifetime[Year]}$$

Where:

- *Grid carbon intensity installation* indicates the grid carbon intensity of the country where the PV system is installed [$gCO_{2\text{-}eq}$/kWh]. In the model, the country-specific grid carbon intensities are obtained from the most recent database published on the website Our World in data (179), providing values for the year 2021.
- *Electricity produced during lifetime* indicates the electricity produced [kWh] over the lifetime of the system computed by Equation 1.
- *Lifetime* indicates the years of lifetime of the PV system considered. The values of the lifetime applied in the model are indicated in Table 5.

5 Evaluation framework application

5.1. Introduction

In line with the methodology presented in Chapter 3, in the current chapter the evaluation framework developed is applied to complete the LCA. The current chapter is divided into three main parts. The first part consists in a selection of five scenarios. Scenarios will be selected to reflect realistic supply chain situations, in terms of the locations where the different components of the PV system are manufactured. The second part presents and analyzes the results obtained for the scenarios selected in the first part. The third part performs sensitivity analyses on a selection of parameters, to discover their influence on the results obtained in the second part.
After this short introduction, the following section will define the scenarios analyzed.

5.2. Definition of scenarios

The different scenarios investigate the effect on impact indicators of the different locations where the manufacturing phases of the PV life cycle can take place. The country of installation is represented by Italy across all scenarios considered. This is due to the following reasons. First, Italy represents an important PV market, being the seventh country worldwide by cumulative installed PV capacity at the end of 2021 (14). Second, installed capacity in Italy is expected to more than double to 2030, reaching 50 GW according to target of the National Energy and Climate Plan (NECP) (10) (8).

The first scenario, named Mixed supply, considers the manufacturing of the various components to take place in different countries.
It is remembered that the modules manufacturing process involves multiple steps, such as the production of wafers, cells, and modules (32). The different steps can happen in different countries (32). As mentioned in Chapter 4, in the developed evaluation framework it is assumed that the manufacturing of modules happens in one single country. The Mixed supply scenario considers the manufacturing of modules to take place in China, the undisputed leader in all steps of the modules production process, holding a share greater than 80% in all manufacturing stages

and accounting for most of the modules imported in Europe (14) (32). The Chinese dominance is expected to persist in the following years, considering the manufacturing plants under construction and planned (32).

The inverter is assumed to be manufactured in Germany, an important manufacturing hub: it is observed that the German firm SMA Solar Technology ranks as the sixth company worldwide for inverter shipment in 2021 (203) and plans to double production capacity at its German headquarters by 2024 (204).

The other BOS components are manufactured in Italy in this scenario. The assumption of sourcing BOS components from the same country of the installation is found in multiple contributions from the literature, such as in Ito et al. (109) and in Rahman et al. (36). As observed in Section 4.4, the other BOS components different than the inverter are represented by the mounting structure and other electrical components, namely cabling and equipment for grid connection. ENF Solar database (205) shows examples of Italian companies active in the manufacturing of mounting structures, such as Sun-age (206) and Sunerg Solar (207). Lastly, the Italian production of cables for PV systems is confirmed by the presence of companies such as Tecnikabel S.p.A. (208) and Enco (209).

Given that in most cases modules and BOS components are imported from different locations (105), the Mixed supply scenario will be also referred to as the reference scenario.

The second scenario, named Chinese supply, considers the manufacturing of all components to happen in China.

Modules are imported from China. China is the undisputed leader in modules manufacturing and accounts for most of the modules imported in Europe (32).

The inverter is produced in China, the global leader in inverter production (15) since accounting for two thirds of worldwide production in 2020. Also, it is observed that China exported 63 GW of inverters in 2021 (14).

The other BOS components different than the inverter are manufactured in China. The relevance of China as a producer of mounting structures can be confirmed by the fact that it is the country with more companies specialized in mounting structures manufacturing according to ENF Solar database (205). Furthermore, it is observed that the Chinese company Grace Solar ranks among the top five companies for PV mounting structures' global market share in 2020, and their products have been installed in over 100 countries (210). Another example shows that the export of mounting structures from China to Europe is realistic: it is observed that two companies ranked among the top five for module shipments worldwide in 2021 (14), and having the majority of their factories in China (211) (212), namely Canadian Solar and Trina Solar, offer also racking solutions bundled with their modules (213). To conclude on the relevance of China also in cables manufacturing, it is observed that that over 35% of the companies specialized in the production of cables for PV applications included in the ENF Solar database are based in China (214).

The third scenario, named Out-of-Asia supply, considers the manufacturing of components to take place outside Asia.
Modules are manufactured in USA, the largest PV modules producer outside Asia in 2020 and 2021 (15) (14). USA represents the fifth country for modules production in 2021 and its output is expected to increase after announcements of President Biden (14). To confirm on the importance of USA in the module manufacturing supply chain, it is observed that it represents the fourth country for polysilicon production in 2021 after China, Germany, and Malaysia (32).
The inverter is produced in Germany in this scenario. As presented for the Mixed supply scenario, Germany is home to one of the largest inverter manufacturers by shipments worldwide.
As in the Mixed supply scenario, the remaining BOS components are manufactured in Italy.

The fourth scenario, named German supply, assumes the manufacturing of all components to happen in Germany.
In 2021, Germany represented the largest producer of PV modules in Europe and the second largest producer of polysilicon worldwide (32). It is observed that a tiny share of modules demand in Europe is satisfied by modules produced in Germany (32). Nevertheless, the German supply scenario is valuable to represent a case with a supply from a European country, in line with the efforts from the European Commission, targeting 30 GW per year of PV manufacturing capacity in the EU across the supply chain by 2025 (215) (216).
As in the Mixed supply and in the Out-of-Asia supply scenarios, the inverter is manufactured in Germany.
The other BOS components different than the inverter are manufactured in Germany. The export from Germany to Italy is considered feasible for two reasons. First, Germany is the European country with more companies active in mounting structures manufacturing according to ENF Solar database (217). Second, the geographical proximity to Italy increases the feasibility of trade between the two countries.

The last scenario, named Italian supply, assumes the manufacturing of all components to happen in Italy. It is observed that this case is rare to happen, given the limited modules production in Italy, corresponding to 88 MW in 2021 for a maximal production capacity of 1144 MW according to the IEA (104). Nevertheless, Italy is chosen as the manufacturing location to evaluate the effect of a local supply chain, in line with the effort of Enel Green Power to increase the output of the 3Sun factory (218). The utility recently signed a grant agreement with the European Commission to increase from 200 MW to 3 GW by 2024 the production capacity of the modules factory located near Catania (218).

The inverter is manufactured in Italy. The assumption is considered plausible, given the inverter production capacity of the country (15). It is mentioned by the IEA that companies producing inverters in Italy include Elettronica Santerno S.p.A, Elpower s.r.l, Borri S.p.A, Fimer S.p.A, Friem S.p.A., and Siel S.p.A (104).

The other BOS components different than the inverter are manufactured in Italy, as in the Mixed supply scenario and in the Out-of-Asia supply scenario.

In all scenarios considered, the transportation of components from the countries of manufacturing to the installation location is completed by trucks for road transportation and by ships for water transportation. The distances are obtained from Google Maps for road transportation and from Searates.com (219) for water transportation. The installation is in Lombardia, the Italian region with the highest installed capacity in 2021, and the second Italian region for cumulative installed capacity at the end of 2021 (220), in the countryside around 30 km east of Milan. As mentioned in Section 4.8, the end-of-life phase is assumed to happen in the same country of the installation. This is considered a realistic assumption given that the trade of PV waste to other countries is considered more likely for countries with a limited installed capacity (99). Furthermore, it is observed that two of the five PV waste recyclers included in the IEA report on modules recycling in Europe are located in Italy (221), showing that the processing of waste PV modules is feasible to happen in Italy. In all scenarios considered, the installation considered is a ground-mounted utility-scale installation. The size of the installation is equal to 1 MW. In addition, in all scenarios the benefits from the end-of-life phase are not considered. The effect of benefits from the end-of-life phase will be assessed in the sensitivity analysis.

All the six PV technologies included in the evaluation framework development chapter will be compared in each scenario. It is assumed the same distance from the manufacturing to the installation location for all technologies. Namely, for every manufacturing country, it is selected a location of production, and it is considered to be the same for all technologies. It is observed that the assumption adopted is not reflecting the reality, since not all factories produce all PV technologies (222). Nevertheless, considering different manufacturing locations for the various PV technologies would increase considerably the complexity, without significantly changing the results, since only the manufacturing location within the same country would vary, affecting the distances to be covered to transport components to the installation location.

Table 12 shows the common values of the input variables for the evaluation framework across all scenarios considered.

Input variables		
Capacity of PV system	[MW]	1
Country of installation	[-]	Italy
End-of-life benefits	[-]	No

Table 12: Common input variables across all scenarios considered (Own production).

Considering the country of installation, namely Italy, it is important to mention its grid carbon intensity, equal to 341 $gCO_{2\text{-}eq}/kWh$ (179) in 2021, and its solar irradiation, equal to 1486 $kWh/(m^2*year)$ (167).
The next subsection will present the assumptions adopted for the first scenario in detail.

5.2.1. Mixed supply scenario

As previously mentioned, the Mixed supply scenario considers modules manufacturing to happen in China. Modules manufacturing is assumed to take place in Jiangsu province, representing the main modules manufacturing hub in China and accounting for 30% of worldwide production (32). Modules are assumed to be transported from the factory of manufacturing to the port of Shanghai by truck, and then by ship to Italy. The distance from the port of Shanghai to be covered by truck is equal to 310 km according to Google Maps. Then, the ship is assumed to transit through the busiest ports of the respective countries, namely Shanghai and Trieste (223) (224). The distance between the two ports is computed thanks to Searates website, and is equal to 15537 km passing from the Suez Canal (219). The distance to be covered by truck from the port of Trieste to the installation location is equal to 386 km (225). The inverter is assumed to be manufactured in Germany at SMA Solar Technology's factory, expected to double its production capacity by 2024 (204). The road distance from the installation location is then equal to 836 km (226). The manufacturing of the other BOS components is assumed to take place in Italy. A generic road distance of 300 km is assumed from the manufacturing to the installation location.

5.2.1.1. Mixed supply scenario: recap of assumptions

Table 13 shows the scenario-specific values of the input variables for the evaluation framework.

Input variables		
Country of modules manufacturing	[-]	China
Modules distance road	[km]	696
Modules distance water	[km]	15537
Inverter country of manufacturing	[-]	Germany
Inverter distance road	[km]	836
Inverter distance water	[km]	0
BOS (except inverter) country of manufacturing	[-]	Italy
BOS (except inverter) distance road	[km]	300
BOS (except inverter) distance water	[km]	0

Table 13: Mixed supply scenario's specific input variables (Own production).

Considering the countries of manufacturing, it is important to mention their grid carbon intensities, equal to 544 $gCO_{2\text{-eq}}$/kWh for China, 366 $gCO_{2\text{-eq}}$/kWh for Germany, and 341 $gCO_{2\text{-eq}}$/kWh for Italy in 2021 (179).

5.2.2. Chinese supply scenario

As previously mentioned, the Chinese supply scenario considers the manufacturing of all components to happen in China. The same distances for modules transportation of the Mixed supply scenario are considered. For BOS components, a road distance of 300 km from the factory of the manufacturing to the port of Shanghai is assumed. Then, BOS components follow the same route as modules, being transported by ship from Shanghai to Trieste, and by truck to the installation location. The distances covered by BOS components are then equal to 15537 km by ship and 686 km by truck.

5.2.2.1. Chinese supply scenario: recap of assumptions

Table 14 shows the scenario-specific values of the input variables for the evaluation framework.

Input variables		
Country of modules manufacturing	[-]	China
Modules distance road	[km]	696
Modules distance water	[km]	15537
inverter country of manufacturing	[-]	China
Inverter distance road	[km]	686
Inverter distance water	[km]	15537
BOS (except inverter) country of manufacturing	[-]	China
BOS (except inverter) distance road	[km]	686
BOS (except inverter) distance water	[km]	15537

Table 14: Chinese supply scenario's specific input variables (Own production).

Considering the country of manufacturing, namely China, it is important to mention its grid carbon intensity, equal to 544 $gCO_{2\text{-eq}}$/kWh (179) in 2021.

5.2.3. Out-of-Asia supply scenario

This scenario considers the manufacturing of components to happen outside Asia. Modules manufacturing is assumed to take place in the largest PV modules factory in the USA, located in Ohio and having a production capacity of 1.8 GW per year (222). Modules are assumed to be transported from the factory of manufacturing to the port of New York by truck, and then by ship to the port of Genova. The distances covered are then equal to 896 km by truck and 7531 km by ship (219). The road distance from the port of Genova to the installation location is computed thanks to Google Maps and is equal to 183 km. Since the inverter is manufactured in Germany, the same distance considered in the Mixed supply scenario is applied. The other BOS components are manufactured in Italy and a generic road distance of 300 km is assumed to transport them to the installation location.

5.2.3.1. Out-of-Asia supply scenario: recap of assumptions

Table 15 shows the scenario-specific values of the input variables for the evaluation framework.

Input variables		
Country of modules manufacturing	[-]	United States
Modules distance road	[km]	1079
Modules distance water	[km]	7531
inverter country of manufacturing	[-]	Germany
Inverter distance road	[km]	836
Inverter distance water	[km]	0
BOS (except inverter) country of manufacturing	[-]	Italy
BOS (except inverter) distance road	[km]	300
BOS (except inverter) distance water	[km]	0

Table 15: Out-of-Asia supply scenario's specific input variables (Own production).

Considering the countries of manufacturing, it is important to mention their grid carbon intensities, equal in 2021 to 379, 366 and 341 $gCO_{2\text{-eq}}$/kWh for USA, Germany, and Italy, respectively (179).

5.2.4. German supply scenario

The German supply scenario considers the manufacturing of all components to take place in Germany. Modules are assumed to be manufactured in Meyer Burger's factory in Freiberg, representing one of the main modules manufacturing plants in

Germany (227), having a yearly production capacity of 0.4 GW and planning expansion to 1 GW (228). The road distance from the manufacturing to the installation location is then equal to 908 km. The distance for the inverter is the same considered in the previous Mixed supply and Out-of-Asia supply scenarios, namely 836 km to be covered by truck. For the other BOS components, a generic road distance of 900 km from the manufacturing to the installation location is assumed.

5.2.4.1. German supply scenario: Recap of assumptions

Table 16 shows the scenario-specific values of the input variables for the evaluation framework.

Input variables		
Country of modules manufacturing	[-]	Germany
Modules distance road	[km]	908
Modules distance water	[km]	0
inverter country of manufacturing	[-]	Germany
Inverter distance road	[km]	836
Inverter distance water	[km]	0
BOS (except inverter) country of manufacturing	[-]	Germany
BOS (except inverter) distance road	[km]	900
BOS (except inverter) distance water	[km]	0

Table 16: German supply scenario's specific input variables (Own production).

Considering the country of manufacturing, namely Germany, it is important to mention its grid carbon intensity, equal to 366 gCO_{2-eq}/kWh in 2021 (179).

5.2.5. Italian supply scenario

The Italian supply scenario considers the manufacturing of all components to take place in Italy. Modules are assumed to be manufactured in the 3Sun plant located near Catania, given that it is one of the largest plants in Italy by modules production capacity in 2021 (14), and it is expected to further grow to 3 GW of production capacity by 2024 (218). The distance from the installation location to be covered by truck is then equal to 1365 km. The inverter is assumed to be manufactured by FIMER, a leading inverter producer in Italy (229), and the eleventh company worldwide by inverter shipments in 2021 (203). Production takes place in the factory located in Vimercate (230). The road distance from the installation location is then equal to 26 km. For the other BOS components, a generic road distance of 300 km from the manufacturing to the installation location is assumed.

5.2.5.1. Italian supply scenario: recap of assumptions

Table 17 shows the scenario-specific values of the input variables for the evaluation framework.

Input variables		
Country of modules manufacturing	[-]	Italy
Modules distance road	[km]	1365
Modules distance water	[km]	0
inverter country of manufacturing	[-]	Italy
Inverter distance road	[km]	26
Inverter distance water	[km]	0
BOS (except inverter) country of manufacturing	[-]	Italy
BOS (except inverter) distance road	[km]	300
BOS (except inverter) distance water	[km]	0

Table 17: Italian supply scenario's specific input variables (Own production).

Considering the country of manufacturing, namely Italy, it is important to mention its grid carbon intensity, equal to 341 gCO$_{2\text{-eq}}$/kWh in 2021 (179).

5.3. Results and discussion

In the current section, the results for each technology will be presented and analyzed. After the presentation of results for all the technologies considered, a comparison of results across technologies and scenarios will be provided.

5.3.1. Monocrystalline

Figure 38 shows the results for the cumulative energy demand.

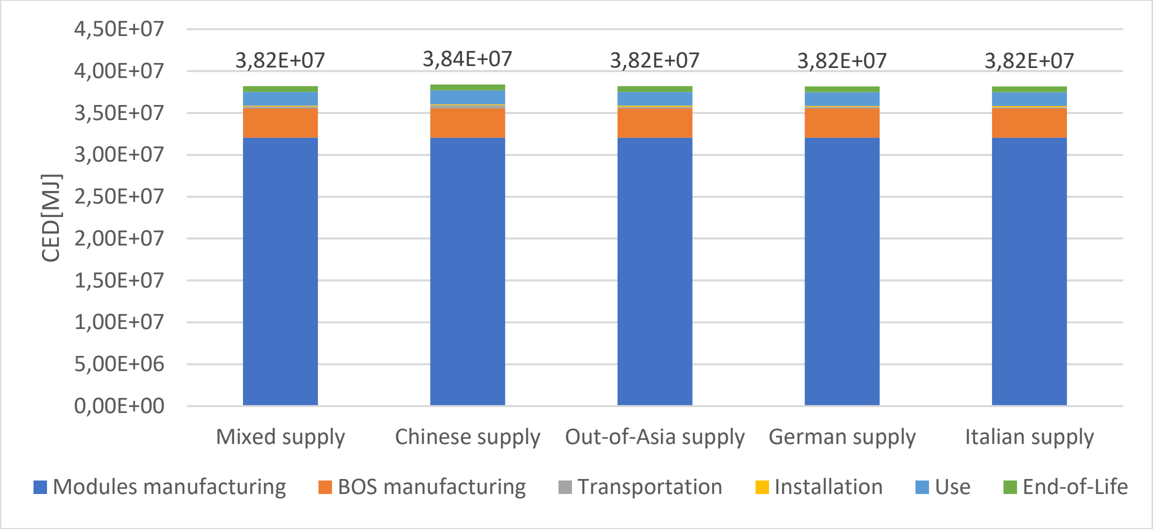

Figure 38: CED results for monocrystalline technology (Own production).

Figure 38 shows a limited variability of the cumulative energy demand across the five scenarios considered. The lowest value of the CED corresponds to the Italian supply scenario and is equal to 3.82*10^7 MJ, while the maximum value corresponds to the Chinese supply scenario and is equal to 3.84*10^7 MJ. The maximum is only 0.59% higher than the minimum. The variation of the CED across scenarios is due to the different distances covered and shares of transport modes considered, impacting the transportation phase as well as the use phase, because of the inverter replacement. As a matter of fact, the transportation phase in the Chinese supply scenario is responsible for a CED more than twice higher than in the Italian supply scenario.

Considering the breakdown into phases, the modules manufacturing phase accounts for over 83.54% of the total CED across all scenarios. The CED of the modules manufacturing phase is equal to 3.21*10^7 MJ across all scenarios. The fact that the module manufacturing is the most impactful phase is confirmed by results from several papers analyzing systems based on monocrystalline technology, such as Ito et al. (109). The BOS manufacturing is the second most impactful phase and accounts from 9.01% to 9.06% of the total CED depending on the scenario. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The use phase is the third most impactful phase, mainly due to the inverter replacement, and accounts for 4.31% or 4.32% of the total CED depending on the scenario. End-of-life phase is responsible for 1.80% or 1.79% of the total impact depending on the scenario considered. The impact of the transportation phase as a percentage with respect to the total CED over the life cycle ranges from 0.48% in the Italian supply scenario to 1.03% in the Chinese supply scenario. Finally, installation is the phase accounting for the lowest impact across all scenarios, being responsible for 0.32% of the total CED.

The results obtained are compared with findings from the literature. First, it has been observed in Subsection 2.2.5 that the values of the impact of the transportation phase encountered in the contributions analyzed are limited, accounting from 0.47% to 4.00% of the total CED over the life cycle except in one contribution indicating the value of 11.00%, as shown by Figure 28. Consequently, it is reasonable that varying the distances covered in the transportation phase has a limited impact on the total CED over the life cycle of the system. Second, selected contributions from the literature, such as Serrano-Lujan et al. (102), assume the primary energy embedded in the modules manufacturing process to remain unchanged while varying the country of manufacturing. Third, Leccisi et al. (125) show that the cumulative energy demand of the modules manufacturing process varies in a limited manner while varying the manufacturing location. In particular, it is estimated from the results shown in a chart by the mentioned authors that the CED of the modules manufacturing process varies around 4% between monocrystalline modules manufactured in China and monocrystalline modules manufactured in Europe adopting 11% of monocrystalline wafers produced in China and 89% of monocrystalline wafers produced in Europe (125).

Figure 39 shows the results for the global warming potential.

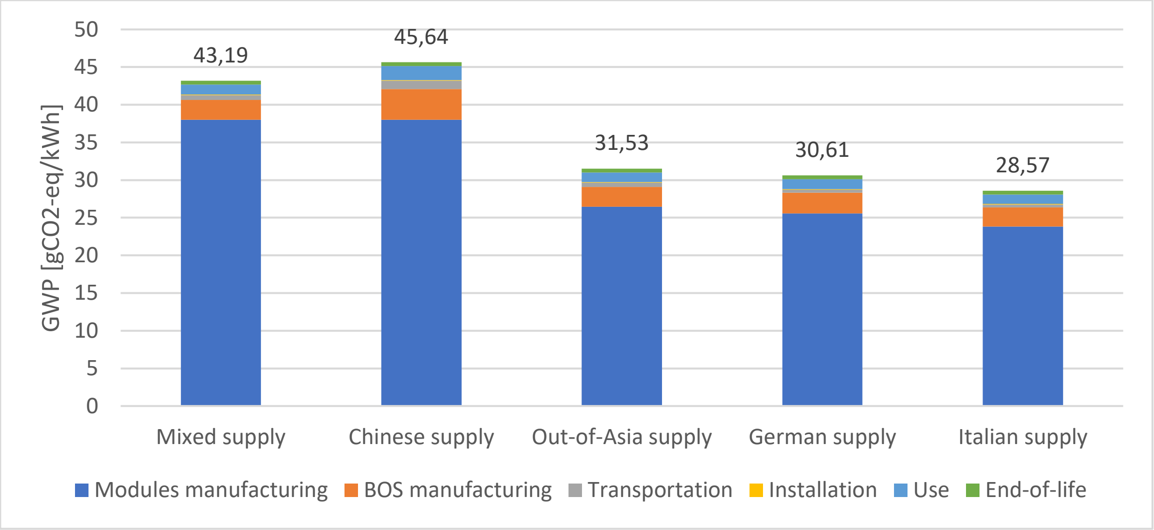

Figure 39: GWP results for monocrystalline technology (Own production).

Figure 39 shows a consistent variation of the global warming potential across scenarios. The maximum value of the GWP corresponds to the Chinese supply scenario, with a GWP of 45.64 $gCO_{2\text{-eq}}$/kWh, while the minimum value corresponds to the Italian supply scenario, with a GWP of 28.57 $gCO_{2\text{-eq}}$/kWh. The maximum is 59.75% higher than the minimum. The differences across scenarios are driven by the variation of the impact of the modules manufacturing phase, accounting for over 83.26% of the impact across all scenarios considered. The variation of the impact of the modules manufacturing phase across scenarios is driven by the different grid carbon intensities of the manufacturing countries. For example, modules manufacturing phase accounts for 38.00 $gCO_{2\text{-eq}}$/kWh when happening in China and for 23.82 $gCO_{2\text{-eq}}$/kWh in case of a production in Italy. The observation is confirmed by selected contributions from the literature analyzing systems based on monocrystalline technology. For example, Murphy and McDonnell (178) observe that the grid carbon intensity of the country where the modules manufacturing takes place is a strong driver for the GHG emissions over the life cycle.

Considering the breakdown into phases, modules manufacturing is responsible for over 83.26% of the impact in all scenarios considered. The fact that the modules manufacturing phase is the most impactful is confirmed by results from several scholars analyzing systems based on monocrystalline technology, such as Kim et al. (80). BOS manufacturing is the second most impactful phase, responsible from 6.11% of the total impact in the Mixed supply scenario to 9.00% in the German supply scenario. Furthermore, it is observed that the GWP of the BOS manufacturing phase ranges from 2.57 $gCO_{2\text{-eq}}$/kWh in the Italian supply scenario to 4.10 $gCO_{2\text{-eq}}$/kWh in the Chinese supply scenario. The variation of the impact is driven by the different grid carbon intensities of the manufacturing countries. This result is in line with Muller et al. (74), where it is observed that the carbon footprint of BOS components more than doubles when the electricity mix used in the production process changes from the European to the Chinese one. The other phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The use phase is the third most impactful phase, responsible for an impact ranging from 3.02% of the total in the Mixed supply scenario to 4.27% in the Italian supply scenario. The transportation phase is responsible for a share of the total GWP ranging from 1.24% in the German supply scenario to 2.41% in the Chinese supply scenario. The end-of-life phase is responsible for the same absolute value of the impact across all scenarios, given that it always takes place in Italy, and accounts from 1.12% of the total impact in the Chinese supply scenario to 1.79% in the Italian supply scenario. The installation phase is the one accounting for the lowest impact in terms of GWP, corresponding to less than 0.32% of the total impact across all scenarios considered.

The numerical values of the GWP reported in Figure 39 are in line with the ranges encountered in the literature. For example, they are included in the range of the GWP for systems based on monocrystalline technology provided in the review from Ludin et al. (78), except for the Italian supply scenario, since the lower bound indicated by the mentioned scholars is 29 $gCO_{2\text{-eq}}$/kWh. This can be justified by the fact that the Italian grid carbon intensity is lower than that of countries most often considered as the manufacturing location in the literature, such as China.

Figure 40 shows the results for the energy payback time.

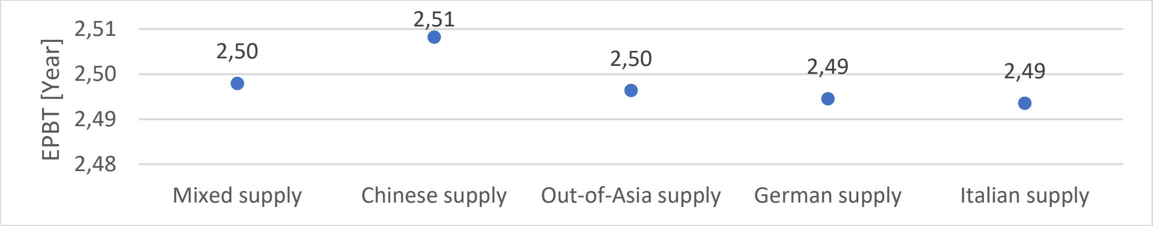

Figure 40: EPBT results for monocrystalline technology (Own production).

Figure 40 shows that the EPBT varies in a negligible manner across scenarios. As a matter of fact, it has been observed while analyzing Figure 38 that the cumulative energy demand grows 0.59% from the minimum value, corresponding to the Italian supply scenario, to the maximum value, corresponding to the Chinese supply scenario. Given that the location of installation and the yearly electricity production are fixed across scenarios, the same result holds true for the EPBT. Namely, it changes 0.59% from the minimum of 2.49 years, corresponding to the Italian supply scenario, to the maximum of 2.51 years, corresponding to the Chinese supply scenario.

The numerical values obtained are in line with selected contributions from the literature. For example, they fall within the ranges of the EPBT for systems based on monocrystalline technology indicated in the reviews from Peng et al. (85) and Ludin et al. (78).

Figure 41 shows the results for the CO_2 payback time.

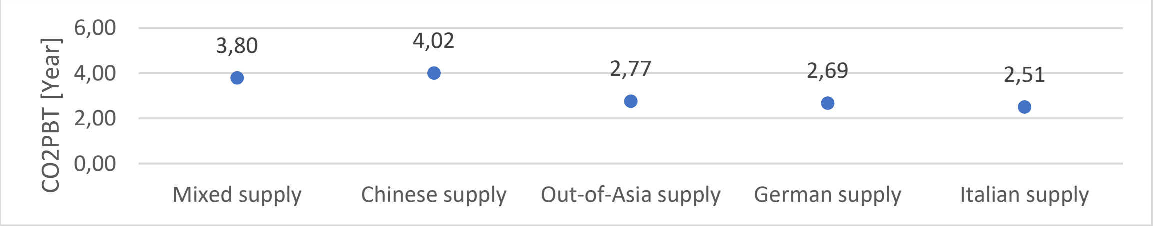

Figure 41: CO_2PBT results for monocrystalline technology (Own production).

Figure 41 shows that the CO_2PBT varies consistently across scenarios. As observed while analyzing Figure 39, the global warming potential grows 59.75% from the minimum value, represented by the Italian supply scenario, to the maximum value, represented by the Chinese supply scenario. It was observed that the main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country of modules manufacturing. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant. Consequently, the same result observed for the GWP holds true for the CO_2PBT. Namely, it grows 59.75% times from the minimum of 2.51 years, represented by the Italian supply scenario, to the maximum of 4.02 years, represented by the Chinese supply scenario. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is the grid carbon intensity of the country of modules manufacturing.

The results obtained are compared with findings from the literature. It is observed in the paper from Mukisa et al. (105), analyzing systems based on multicrystalline technology, that for a fixed location of installation, the variation of the CO_2PBT can be attributed mainly to the grid carbon intensity of the country of modules manufacturing. The results obtained suggest that the observation from the mentioned scholars holds true also for systems based on monocrystalline technology.

5.3.2. Multicrystalline

Figure 42 shows the results for the cumulative energy demand.

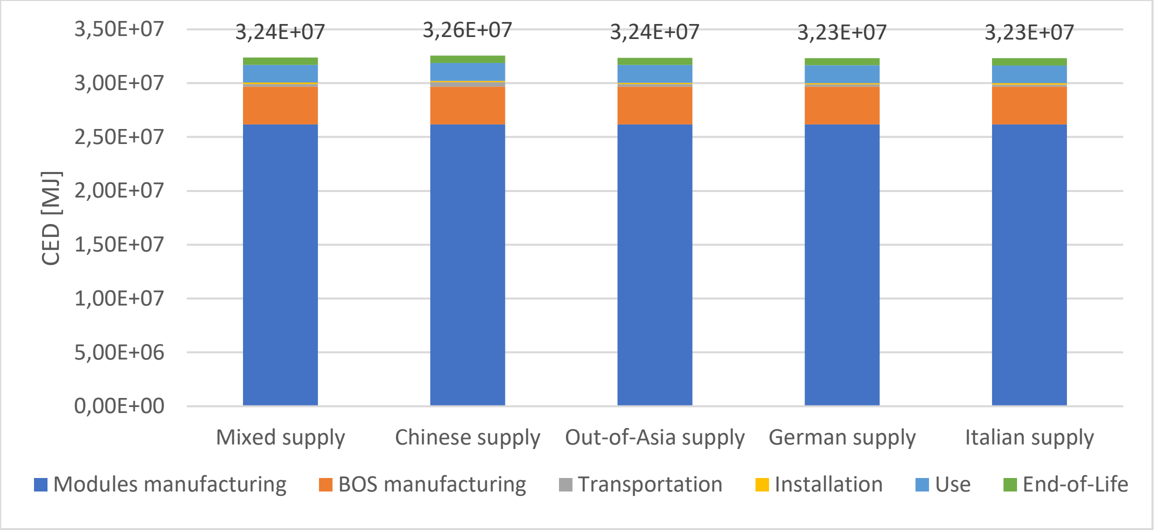

Figure 42: CED results for multicrystalline technology (Own production).

Figure 42 shows a limited variability of the cumulative energy demand across the five scenarios considered. The lowest value of the CED correspond to the Italian supply scenario and is equal to 3.23*10^7 MJ, while the maximum value corresponds to the Chinese supply scenario and is equal to 3.26*10^7 MJ. It is observed that the maximum is only 0.71% higher than the minimum. The variation of the CED across scenarios is due to the different distances and share of transport modes considered, impacting the transportation phase as well as the use phase, because of the inverter replacement. As a matter of fact, the transportation phase in the Chinese supply scenario is responsible for a CED more than twice higher than in the Italian supply scenario.

Considering the breakdown into phases, the modules manufacturing phase accounts for over 80.36% of the total CED across all scenarios. The CED of the modules manufacturing phase is equal to 2.62*10^7 MJ across all scenarios. The fact that the modules manufacturing phase is the most impactful is confirmed by several contributions from the literature analyzing systems based on multicrystalline technology, such as the one from Nordin et al. (83). The BOS manufacturing is the second most impactful phase and accounts from 10.81% to 10.89% of the total CED depending on the scenario considered. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The use phase is the third most impactful phase, mainly due to the inverter replacement, and accounts from 5.11% to 5.13% of the total CED depending on the scenario. End-of-life phase is responsible from 2.07% to 2.09% of the total CED across all scenarios. The transportation phase is responsible for a share of the total CED ranging from 0.59% in the Italian supply scenario to 1.25% in the Chinese supply scenario. The installation phase is the one accounting for the lowest impact, corresponding to 0.39% of the total CED across all scenarios.

The results obtained are compared with findings from the literature. First, it has been observed in Subsection 2.2.5 that the values of the impact of the transportation phase encountered in the contributions analyzed are limited, accounting from 0.47% to 4.00% of the total CED over the life cycle except in one contribution indicating the value of 11.00%, as shown by Figure 28. Consequently, it is reasonable that varying the distances covered in the transportation phase has a limited impact on the total CED over the life cycle of the system. Second, selected contributions from the literature, such as Serrano-Lujan et al. (102), assume the primary energy embedded in the modules manufacturing process to remain unchanged while varying the country of manufacturing. Third, it is observed that Gurzenich and Wagner (231), considering the differences in the CED while varying the country where the life cycle of the PV system takes place, comprehensive of manufacturing, installation, and operation, compute that the CED of a system adopting multicrystalline technology varies around 3% while changing the location where the life cycle takes place across five different European countries, namely Italy, France, Germany, Spain, and Netherlands, since in the mentioned paper the country indicated are characterized by similar values of the efficiency of the electricity supply, indicating the ratio of the electricity output to the primary energy supply.

Figure 43 shows the results for the global warming potential.

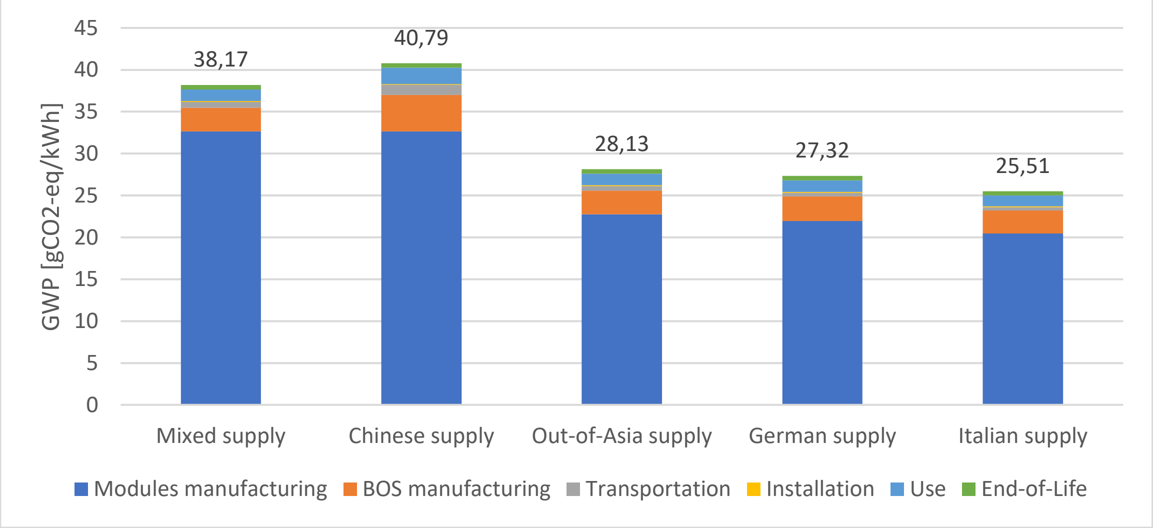

Figure 43: GWP results for multicrystalline technology (Own production).

Figure 43 shows a consistent variation of the global warming potential across scenarios. The GWP ranges from a minimum of 25.51 $gCO_{2\text{-eq}}$/kWh in the Italian supply scenario to a maximum of 40.79 gCO_{2-eq}/kWh in the Chinese supply scenario. The maximum is 59.85% times higher than the minimum. The differences in the GWP across scenarios are driven by the variation of the impact of the modules manufacturing phase, accounting for over 80.00% of the impact across all scenarios considered. The variation of the impact of the modules manufacturing phase across scenarios is driven by the different grid carbon intensities of the manufacturing countries. For example, modules manufacturing phase accounts for 32.63 gCO_{2-eq}/kWh when happening in China and for 20.45 gCO_{2-eq}/kWh in case of a production in Italy. The findings are compared to contributions from the literature analyzing systems based on multicrystalline technology. For example, Dones and Frischknecht (232) observe that most of the impact of PV systems in terms of global warming potential originates from the electricity requirements in the manufacturing process. Consequently, it is rational that the grid carbon intensity of the modules manufacturing country is a strong driver of the global warming potential.

Considering the breakdown into phases, modules manufacturing is responsible for the highest impact, accounting for over 80.00% of the total GWP across all scenarios considered. The fact that modules manufacturing is the most impactful phase is confirmed by results from several scholars analyzing systems based on multicrystalline technology, such as Hou et al. (132). The BOS manufacturing is the second most impactful phase, responsible from 7.41% of the total impact in the Mixed supply scenario to 10.81% in the German supply scenario. The GWP of the BOS manufacturing phase ranges from 2.75 gCO_{2-eq}/kWh in the Italian supply scenario to 4.39 gCO_{2-eq}/kWh in the Chinese supply scenario. The variation of the impact is driven by the different grid carbon intensities of the manufacturing countries. This result is in line with Muller et al. (74), where it is observed that the carbon footprint of BOS components more than double when the electricity mix used in the production process changes from the European to the Chinese one. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and indicated in Subsection 2.2.5. The use phase is the third most impactful phase, responsible for an impact ranging from 3.61% of the total GWP in the Mixed supply scenario to 5.06% of the total GWP in the Italian supply scenario. The transportation phase is responsible for a share of the total GWP ranging from 1.51% in the German supply scenario to 2.94% in the Chinese supply scenario. The end-of-life phase is responsible for the same absolute value of the impact across all scenarios, given that it always takes place in Italy, and accounts from 1.29% of the total GWP in the Chinese supply scenario to 2.07% in the Italian supply scenario. The installation is the phase responsible for the lowest impact, ranging from 0.26% to 0.39% of the total GWP depending on the scenario considered.

The numerical values of the GWP reported in Figure 43 fall within the ranges encountered in the literature. For example, they are included in the ranges of the GWP for systems based on multicrystalline technology provided in the reviews from Ludin et al. (78) and Peng et al. (85).

Figure 44 shows the results for the energy payback time.

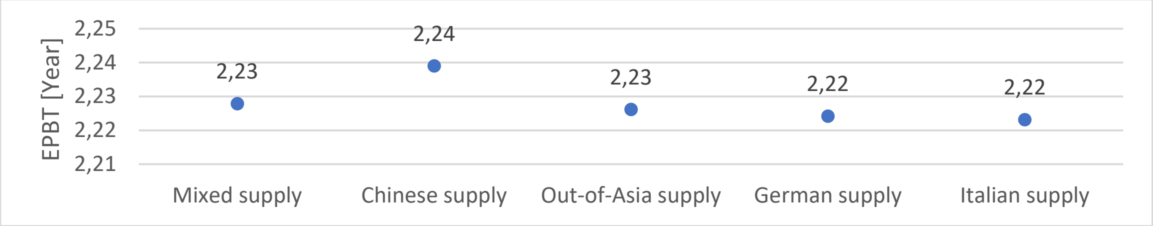

Figure 44: EPBT results for multicrystalline technology (Own production).

Figure 44 shows that the EPBT varies in a negligible manner across scenarios. As a matter of fact, as observed while analyzing Figure 42, the cumulative energy demand grows 0.71% from the minimum value, corresponding to the Italian supply scenario, to the maximum value, corresponding to the Chinese supply scenario. Given that the location of installation and the yearly electricity production are the same across scenarios, the same result holds true for the EPBT. Namely, it changes 0.71% from the minimum of 2.22 years, corresponding to the Italian supply scenario, to the maximum of 2.24 years, corresponding to the Chinese supply scenario.
The numerical values obtained are included in the ranges of the EPBT for systems based on multicrystalline technology indicated in the reviews from Peng et al. (85) and Ludin et al. (78).

Figure 45 shows the results for the CO_2 payback time.

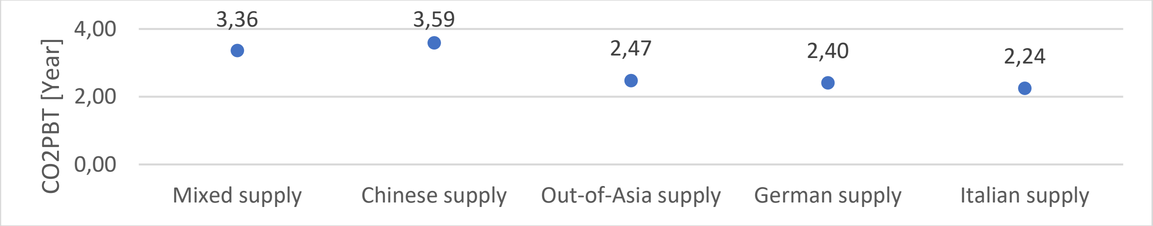

Figure 45: CO_2PBT results for multicrystalline technology (Own production).

Figure 45 shows that the CO_2PBT varies consistently across scenarios. As shown while analyzing Figure 43, the global warming potential grows 59.85% from the minimum value, represented by the Italian supply scenario, to the maximum value, represented by the Chinese supply scenario. It was observed that the main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country of modules manufacturing. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant.

Consequently, the same result observed for the GWP holds true for the CO_2PBT. Namely, it grows 59.85% times from the minimum of 2.24 years, corresponding to the Italian supply scenario, to the maximum of 3.59 years, corresponding to the Chinese supply scenario. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is the grid carbon intensity of the country of modules manufacturing.

The results obtained are compared with findings from the literature. For example, it is observed in the paper from Mukisa et al. (105) that, for a fixed location of installation of a system based on multicrystalline technology, the variation of the CO_2PBT can be attributed mainly to the grid carbon intensity of the country of modules manufacturing.

5.3.3. a-Si

Figure 46 shows the results for the cumulative energy demand.

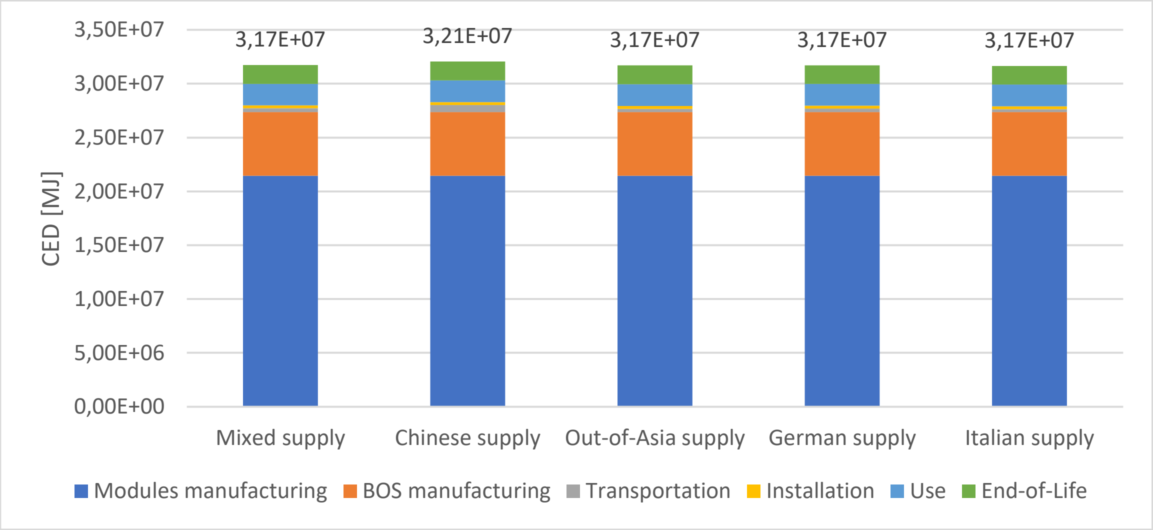

Figure 46: CED results for a-Si technology (Own production).

Figure 46 shows a limited variability of the cumulative energy demand across the scenarios considered. The minimum value of the CED corresponds to the Italian supply scenario and is equal to 3.17*10^7 MJ, while the maximum value corresponds to the Chinese supply scenario and is equal to 3.21*10^7 MJ. The maximum is only 1.27% higher than the minimum. The variation of the CED across scenarios is due to the different distances and share of transport modes considered, impacting the transportation phase as well as the use phase, because of the inverter replacement. As a matter of fact, the transportation phase in the Chinese supply scenario is responsible for a CED 2.46 times higher than in the Italian supply scenario.

Considering the breakdown into phases, the modules manufacturing phase accounts for over 66.88% of the total CED across all scenarios. The CED of the modules manufacturing phase is equal to 2.14*10^7 MJ across all scenarios. The fact that modules manufacturing is the most impactful phase is confirmed by results from several scholars analyzing systems based on a-Si technology, such as Ito et al. (151). BOS manufacturing is the second most impactful phase, accounting from 18.47% of the total CED in the Chinese supply scenario to 18.70% of the total CED in the Italian supply scenario. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The use phase is the third most impactful phase, mainly due to the inverter replacement, and accounts from 6.32% to 6.37% of the total CED depending on the scenario considered. End-of-life phase is responsible from 5.45% to 5.52% of the total CED depending on the scenario. The transportation phase is responsible for a share of the total impact ranging from 0.84% in the Italian supply scenario to 2.05% in the Chinese supply scenario. Finally, installation is the phase characterized by the lowest impact, corresponding to 0.84% or to 0.83% of the total CED depending on the scenario.

The results obtained are compared with findings from the literature. First, it has been observed in Subsection 2.2.5 that the values of the impact of the transportation phase encountered in the contributions analyzed are limited, accounting from 0.47% to 4.00% of the total CED over the life cycle except in one contribution indicating the value of 11.00%, as shown by Figure 28. Consequently, it is reasonable that varying the distances covered in the transportation phase has a limited impact on the total CED over the life cycle of the system. Second, selected contributions from the literature, such as Serrano-Lujan et al. (102), assume the primary energy embedded in the modules manufacturing process to remain unchanged while varying the country of manufacturing.

Figure 47 shows the results for the global warming potential.

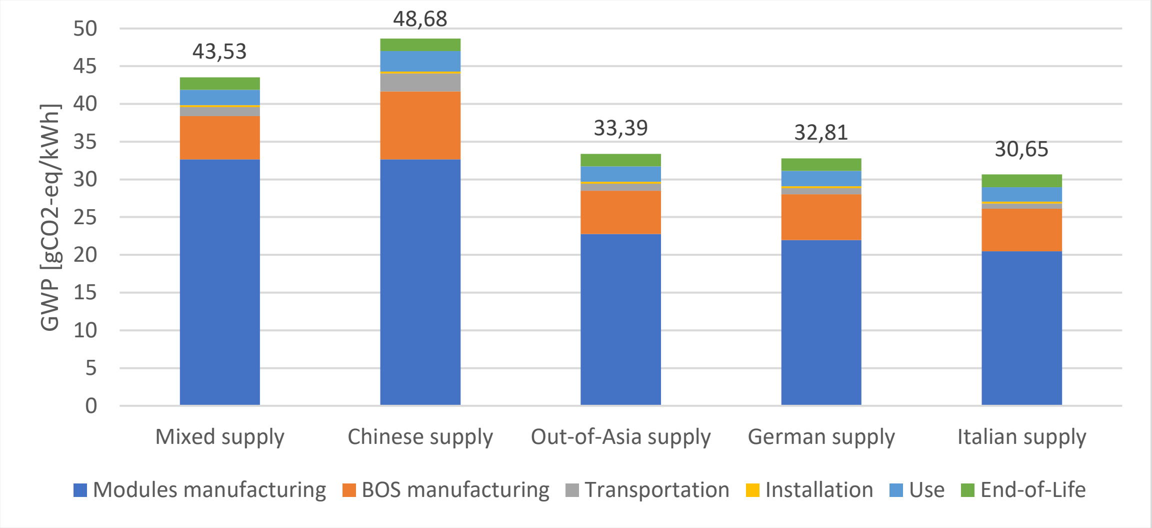

Figure 47: GWP results for a-Si technology (Own production).

Figure 47 shows a consistent variation of the global warming potential across scenarios. The least polluting scenario is the Italian supply scenario, totaling 30.65 $gCO_{2\text{-eq}}$/kWh, while the Chinese supply scenario is the most polluting one, emitting 58.85% more than the Italian supply scenario, namely 48.68 $gCO_{2\text{-eq}}$/kWh. The differences across scenarios are driven by the variation of the impact of the modules manufacturing phase, accounting for over 67.09% of the impact across all scenarios considered. The variation of the impact of the modules manufacturing phase across scenarios is driven by the different grid carbon intensities of the manufacturing countries. For example, modules manufacturing phase accounts for 32.66 $gCO_{2\text{-eq}}$/kWh when happening in China and for 20.47 $gCO_{2\text{-eq}}$/kWh in case of a production in Italy. The results obtained are compared with contributions from the literature analyzing systems based on a-Si technology. For example, Fthenakis and Kim (233) observe that electricity is the main contributor to the primary energy requirements of the modules manufacturing process. Consequently, the global warming potential varies significantly depending on the grid carbon intensity of the country of modules production (113).

Considering the breakdown into phases, modules manufacturing is responsible for a share of the total GWP ranging from 66.80% in the Italian supply scenario to 75.02% in the Mixed supply scenario. BOS manufacturing is the second most impactful phase, responsible from 13.20% of the total GWP in the Mixed supply scenario to 18.52% in the Chinese supply scenario. The GWP of the BOS manufacturing phase ranges from 5.65 $gCO_{2\text{-eq}}$/kWh in the Italian supply scenario to 9.02 $gCO_{2\text{-eq}}$/kWh in the Chinese supply scenario. The variation of the impact is driven by the different grid carbon intensities of the manufacturing countries. This result is in line with Muller et al. (74), where it is observed that the carbon footprint of BOS components more than doubles when the electricity mix used in the production process changes from the European to the Chinese one. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and indicated in Subsection 2.2.5. The use phase is the third most impactful phase, being responsible for a share of the total GWP ranging from 4.66% in the Mixed supply scenario to 6.27% in the Italian supply scenario. The transportation phase is responsible for an impact ranging from 2.21% of the total GWP in the Italian supply scenario to 4.85% in the Chinese supply scenario. The end-of-life phase is responsible for the same absolute value of the impact across all scenarios, given that it always takes place in Italy, and accounts from 3.43% of the total GWP in the Chinese supply scenario to 5.44% in the Italian supply scenario. The installation phase is the one accounting for the lowest impact in terms of GWP, corresponding to less than 0.83% of the total impact over the full life cycle across all scenarios considered.

To conclude, it is observed that the numerical values of the GWP reported in Figure 47 fall within the ranges encountered in the literature. For example, they are included in the ranges of the GWP for systems based on a-Si technology provided in the reviews from Ludin et al. (78) and Peng et al. (85).

Figure 48 shows the results for the energy payback time.

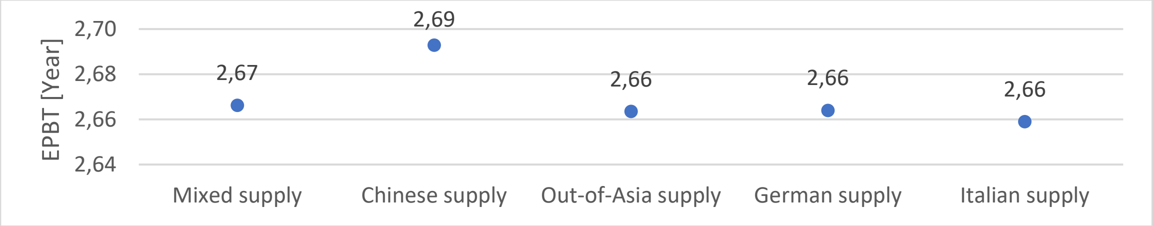

Figure 48: EPBT results for a-Si technology (Own production).

Figure 48 shows that the EPBT varies in a negligible manner across scenarios. As a matter of fact, as observed while analyzing Figures 46, the cumulative energy demand grows 1.27% from the minimum value, corresponding to the Italian supply scenario, to the maximum value, corresponding to the Chinese supply scenario. Given that the location of installation and the yearly electricity production are the same across all scenarios, the same result holds true for the EPBT. Namely, it changes 1.27% from the minimum of 2.66 years, corresponding to the Italian supply scenario, to the maximum of 2.69 years, corresponding to the Chinese supply scenario.

The numerical values obtained fall within the ranges of the EPBT for systems based on a-Si technology indicated in the reviews from Peng et al. (85) and Ludin et al. (78).

Figure 49 shows the results for the CO_2 payback time.

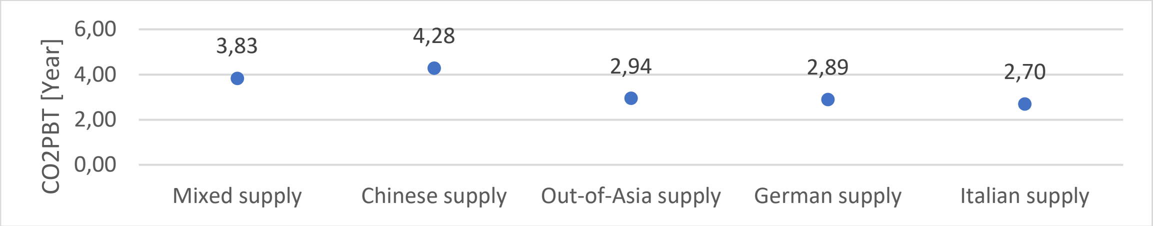

Figure 49: CO_2PBT results for a-Si technology (Own production).

Figure 49 shows that the CO_2PBT varies consistently across scenarios. As observed when analyzing Figure 47, the global warming potential grows 58.85% from the minimum value, represented by the Italian supply scenario, to the maximum value, represented by the Chinese supply scenario. It was observed that the main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country of modules manufacturing. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant. Consequently, the same result observed for the GWP holds true for the CO_2PBT. Namely, it grows 58.85% from the minimum of 2.70 years, represented by the Italian supply scenario, to the maximum of 4.28 years, represented by the Chinese supply scenario. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is the grid carbon intensity of the country of modules manufacturing.

The results obtained are compared with findings from the literature. It is observed in the contribution from Mukisa et al. (105), analyzing systems based on multicrystalline technology, that for a fixed location of installation, the variation of the CO_2PBT can be attributed mainly to the grid carbon intensity of the country of modules manufacturing. The results obtained suggest that the observation from the mentioned scholars holds true also for systems based on a-Si technology.

5.3.4. CIS

Figure 50 shows the results for the cumulative energy demand.

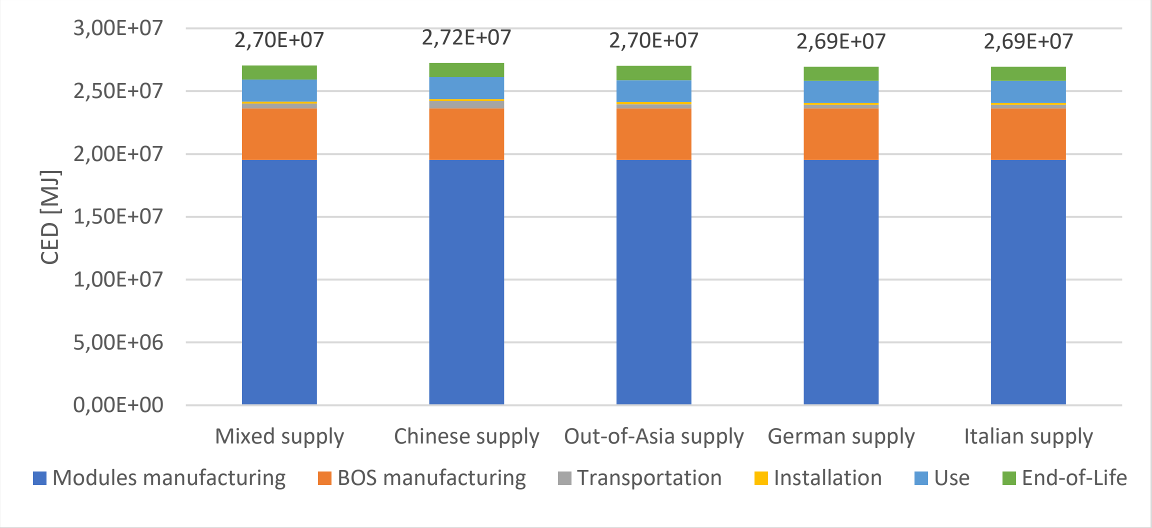

Figure 50: CED results for CIS technology (Own production).

Figure 50 shows a limited variability of the cumulative energy demand across the scenarios considered. The minimum value of the CED corresponds to the German supply scenario and is equal to 2.69*10^7 MJ, while the maximum value of the CED corresponds to the Chinese supply scenario and is equal to 2.72*10^7 MJ. It is observed that the maximum is only 1.14% higher than the minimum. The variation of the CED across scenarios is due to the different distances and shares of transport modes considered, impacting the transportation phase as well as the use phase, because of the inverter replacement. For example, the transportation phase in the Chinese supply scenario is responsible for a CED more than twice higher than in the German supply scenario.

Considering the breakdown into phases, the modules manufacturing phase accounts for over 71.67% of the total CED across all scenarios. The CED of the modules manufacturing phase is equal to 1.95*10^7 MJ across all scenarios. The fact that the modules manufacturing phase is the most impactful is confirmed by results from several contributions analyzing systems based on CIS technology, such as the one from Ito et al. (109). BOS manufacturing is the second most impactful phase, accounting from 15.01% to 15.18% of the total CED depending on the scenario considered. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The use phase is the third most impactful phase, due to the inverter replacement, and accounts from 6.43% to 6.47% of the total CED depending on the scenario. End-of-life phase is responsible from 4.14% to 4.19% of the total impact over the life cycle depending on the scenario.

The transportation phase is responsible for a share of the total CED ranging from 1.07% in the German supply scenario to 2.16% in the Chinese supply scenario. The installation phase is the one accounting for the lowest share of the total CED, equal to 0.59% in all scenarios considered.

The results obtained are compared with findings from the literature. First, it has been observed in Subsection 2.2.5 that the values of the impact of the transportation phase encountered in the literature analyzed are limited, accounting from 0.47% to 4.00% of the total CED over the life cycle except in one contribution indicating the value of 11.00%, as shown by Figure 28. Consequently, it is reasonable that varying the distances covered in the transportation phase has a limited impact on the total CED over the life cycle of the system. Second, selected contributions from the literature, such as Serrano-Lujan et al. (102), assume the primary energy embedded in the modules manufacturing process to remain unchanged while varying the country of manufacturing.

Figure 51 shows the results for the global warming potential.

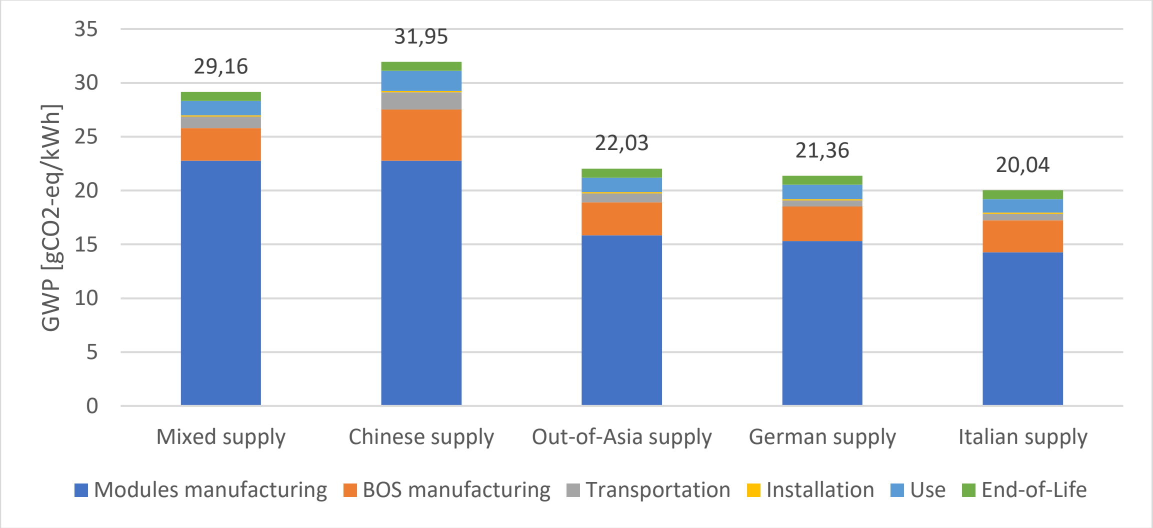

Figure 51: GWP results for CIS technology (Own production).

Figure 51 shows a consistent variation of the global warming potential across scenarios. The least polluting scenarios is the Italian supply scenario, totaling 20.04 $gCO_{2\text{-eq}}$/kWh, while the Chinese supply scenario is the most polluting one, emitting 59.48% more than the Italian supply scenario, namely 31.95 $gCO_{2\text{-eq}}$/kWh. The differences across scenarios are driven by the variation of the impact of the modules manufacturing phase, accounting for over 71.18% of the impact across all scenarios. The variation of the impact of the modules manufacturing phase across scenarios is driven by the different grid carbon intensities of the manufacturing countries. For example, modules manufacturing phase accounts for 22.75 $gCO_{2\text{-eq}}$/kWh when happening in China and for 14.26 $gCO_{2\text{-eq}}$/kWh in case of a production in Italy. The results obtained are compared to contributions from the literature analyzing systems based on CIS technology. For example, Resalati et al. (68) observe that most of the impact in terms of $CO_{2\text{-eq}}$ emissions of CIS cells manufacturing is due to electricity consumption. Given the observation from the scholars, it is reasonable that the grid carbon intensity of the modules manufacturing country is a strong driver of the GWP.

Considering the breakdown into phases, modules manufacturing is responsible for over 71.78% of the total GWP across all scenarios. The fact that the modules manufacturing is the most impactful phase is confirmed by results from several scholars analyzing systems based on CIS technology, such as Ito et al. (151). BOS manufacturing is the second most impactful phase, responsible from 10.49% of the total impact in the Mixed supply scenario to 15.00% in the German supply scenario. The GWP of the BOS manufacturing phase ranges from 2.99 $gCO_{2\text{-eq}}$/kWh in the Italian supply scenario to 4.76 $gCO_{2\text{-eq}}$/kWh in the Chinese supply scenario. The variation of the impact is driven by the different grid carbon intensities of the manufacturing countries. This result is in line with Muller et al. (74), where it is observed that the carbon footprint of BOS components more than doubles when the electricity mix used in the production process changes from the European to the Chinese one. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and indicated in Subsection 2.2.5. The use phase is the third most impactful phase, responsible for a share of the total GWP ranging from 4.64% in the Mixed supply scenario to 6.34% in the Italian supply scenario. The transportation phase is responsible for an impact ranging from 2.61% of the total GWP in the German supply scenario to 5.06% in the Chinese supply scenario. The end-of-life phase is responsible for the same absolute value of the impact across all scenarios, given that it always takes place in Italy, and accounts from 2.58% of the total impact in the Chinese supply scenario to 4.12% in the Italian supply scenario. The installation is the phase accounting for the lowest impact in terms of GWP, corresponding to less than 0.58% of the total impact across all scenarios considered. The numerical values of the GWP reported in Figure 51 are in line with selected contributions from the literature. For example, they are included in the range of the GWP for PV systems adopting CIS technologies provided in the review from Peng et al. (85).

Figure 52 shows the results for the energy payback time.

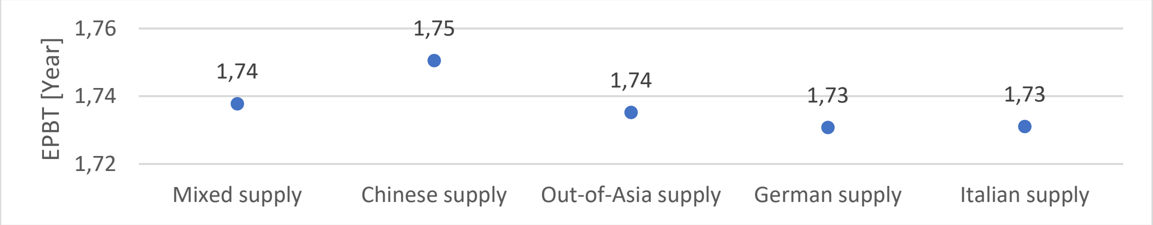

Figure 52: EPBT results for CIS technology (Own production).

Figure 52 shows that the EPBT varies in a negligible manner across scenarios. As a matter of fact, it has been observed while analyzing Figure 50 that the cumulative energy demand varies 1.14% from the minimum value, corresponding to the German supply scenario, to the maximum value, corresponding to the Chinese supply scenario. Given that the location of installation and the yearly electricity production are the same across scenarios, the same result holds true for the EPBT. Namely, it changes 1.14% from the minimum of 1.73 years, corresponding to the German supply scenario, to the maximum of 1.75 years, corresponding to the Chinese supply scenario.
It is observed that the numerical values obtained fall within the ranges of the EPBT for PV systems adopting CIS technology indicated in the reviews from Peng et al. (85) and Ludin et al. (78).

Figure 53 shows the results for the CO_2 payback time.

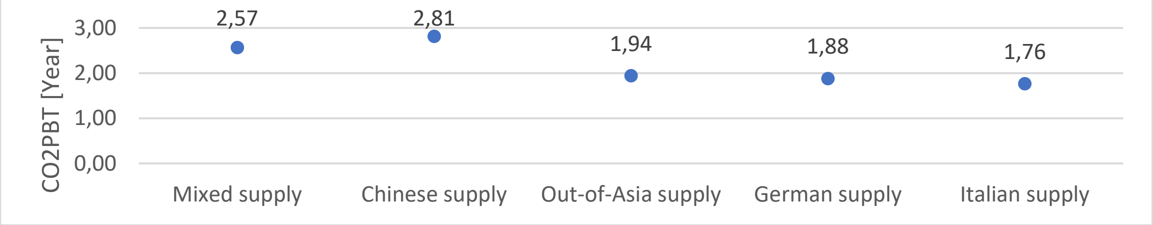

Figure 53: CO_2PBT results for CIS technology (Own production).

Figure 53 shows that the CO_2PBT varies consistently across scenarios. As observed while analyzing Figure 51, the global warming potential grows 59.48% from the minimum value, represented by the Italian supply scenario, to the maximum value, represented by the Chinese supply scenario. It was observed that the main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country of modules manufacturing. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant. Consequently, the same result observed for the GWP holds true for the CO_2PBT. Namely, it grows 59.48% from the minimum of 1.76 years, represented by the Italian supply scenario, to the maximum of 2.81 years, represented by the Chinese supply scenario. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is the grid carbon intensity of the country of modules manufacturing.

The results obtained are compared with findings from the literature. It is observed in the contribution from Mukisa et al. (105), analyzing systems based on multicrystalline technology, that for a fixed location of installation, the variation of the CO_2PBT can be mainly attributed to the grid carbon intensity of the country of modules manufacturing. The results obtained suggest that the observation from the mentioned scholars holds true also for systems based on CIS technology.

5.3.5. CdTe

Figure 54 shows the results for the cumulative energy demand.

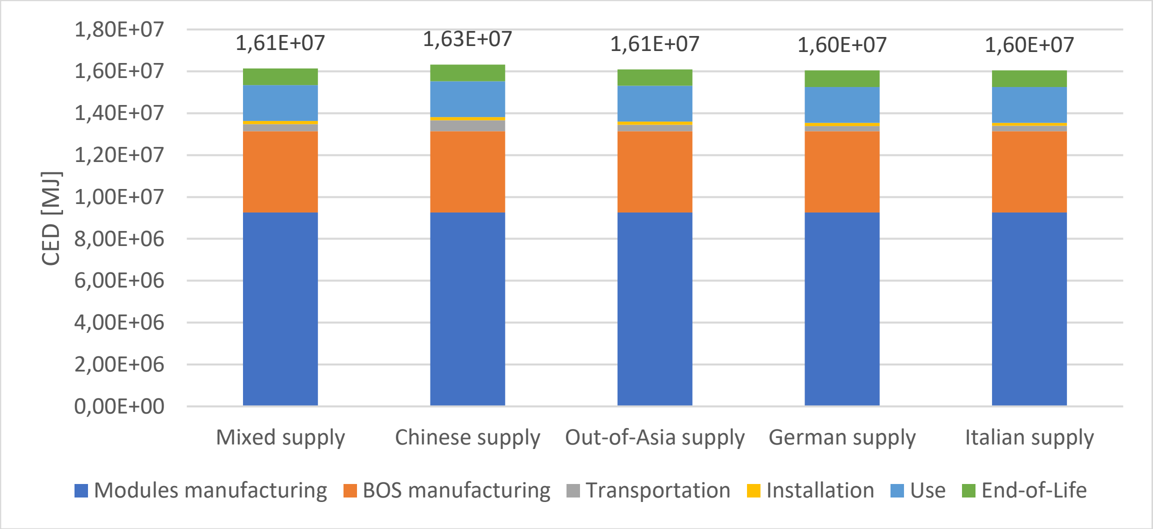

Figure 54: CED results for CdTe technology (Own production).

Figure 54 shows a limited variability of the cumulative energy demand across the scenarios considered. The minimum value of the CED corresponds to the Italian supply scenario and is equal to 1.60*10^7 MJ, while the maximum value corresponds to the Chinese supply scenario and is equal to 1.63*10^7 MJ. It is observed that the maximum is only 1.73% higher than the minimum. The variation across scenarios is due to the different distances covered and share of transport modes considered, impacting the transportation phase as well as the use phase, because of the inverter replacement. For example, the transportation phase in case of the Chinese supply scenario is responsible for a CED more than twice higher than in the Italian supply scenario.

Considering the breakdown into phases, the modules manufacturing phase accounts for over 56.74% of the total CED across all scenarios. The CED of the modules manufacturing phase is equal to 0.96*10^7 MJ across all scenarios. The fact that the modules manufacturing phase is the most impactful is confirmed by results from several scholars analyzing systems based on CdTe technology, such as Held and Ilg (62). BOS manufacturing is the second most impactful phase, responsible from 23.76% to 24.17% of the total CED depending on the scenario. The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The use phase is the third most impactful phase, mainly due to the inverter replacement, and accounts from 10.53% to 10.67% of the total CED depending on the scenario. End-of-life phase is responsible from 4.85% to 4.93% of the total impact depending on the scenario considered. The transportation phase is responsible for a share of the total CED ranging from 1.60% in the German supply scenario to 3.21% in the Chinese supply scenario. The impact of the installation phase is the lowest and corresponds to less than 0.92% of the total CED across all scenarios considered.

The results obtained are compared with findings from the literature. First, it has been observed in Subsection 2.2.5 that the values of the impact of the transportation phase encountered in the sample analyzed are limited, accounting from 0.47% to 4.00% of the total CED over the life cycle except in one contribution indicating the value of 11.00%, as shown by Figure 28. Consequently, it is reasonable that varying the distances covered in the transportation phase has a limited impact on the total CED over the life cycle of the system. Second, selected contributions from the literature, such as Serrano-Lujan et al. (102), assume the primary energy embedded in the modules manufacturing process to remain unchanged while varying the country of manufacturing.

Figure 55 shows the results for the global warming potential.

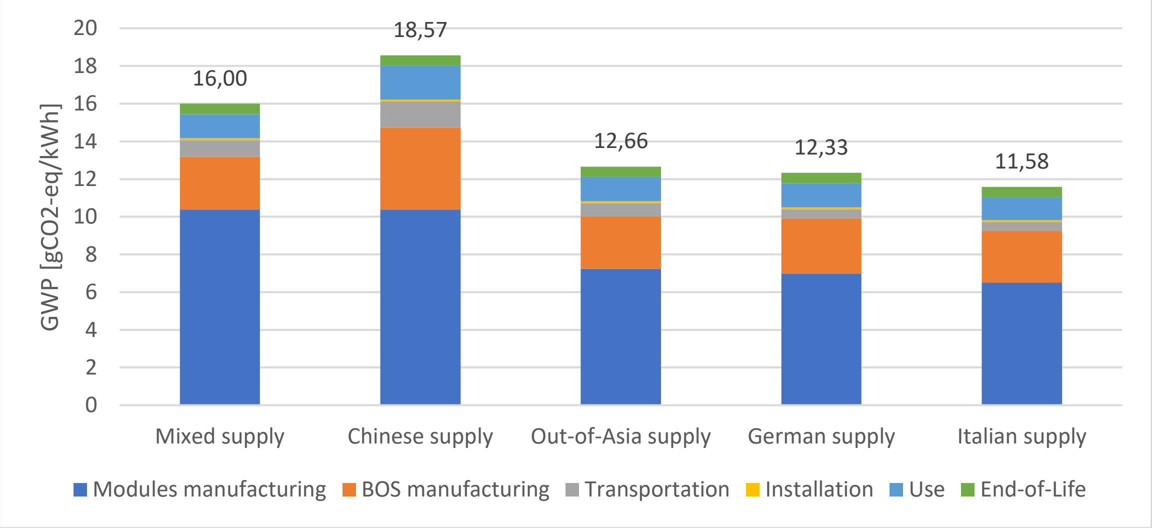

Figure 55: GWP results for CdTe technology (Own production).

Figure 55 shows a consistent variation of the global warming potential across scenarios. The least polluting scenarios is the Italian supply scenario, totaling 11.58 $gCO_{2\text{-eq}}$/kWh, while the Chinese supply is the most polluting scenario, emitting 60.34% more than the Italian supply scenario, namely 18.57 $gCO_{2\text{-eq}}$/kWh. The differences across scenarios are driven by the variation of the impact of the modules manufacturing phase, accounting for over 55.94% of the total GWP across all scenarios considered. The variation of the impact of the modules manufacturing phase across scenarios is driven by the different grid carbon intensities of the manufacturing countries. For example, modules manufacturing phase accounts for 10.39 $gCO_{2\text{-eq}}$/kWh when happening in China and for 6.51 $gCO_{2\text{-eq}}$/kWh in case of a production in Italy. It is confirmed by selected contributions from the literature analyzing systems based on CdTe technology, such as the one from Held and Ilg (62), that electricity consumption in the modules manufacturing process represents the main contributor to the $CO_{2\text{-eq}}$ emissions of the phase. Consequently, it is reasonable that the grid carbon intensity of the modules manufacturing country is a strong driver of the GWP.

Considering the breakdown into phases, modules manufacturing is responsible for over 55.94% of the total GWP across all scenarios considered. The fact that the modules manufacturing phase is the most impactful is confirmed by results from scholars analyzing systems based on CdTe technology, such as Held and Ilg (62). BOS manufacturing is the second most impactful phase, responsible for a share of the total GWP ranging from 17.46% in the Mixed supply scenario to 23.73% in the German supply scenario. Furthermore, it is observed that the GWP of the BOS manufacturing phase ranges from 2.73 $gCO_{2\text{-eq}}$/kWh in the Italian supply scenario to 4.35 $gCO_{2\text{-eq}}$/kWh in the Chinese supply scenario. The variation of the impact is driven by the different grid carbon intensities of the manufacturing countries. This result is in line with Muller et al. (74), where it is observed that the carbon footprint of BOS components more than double when the electricity mix used in the production process changes from the European to the Chinese one. The use phase is the third most impactful phase, responsible for a share of the total impact ranging from 7.99% in the Mixed supply scenario to 10.37% in the German supply scenario. The transportation phase is responsible for a share of the total GWP ranging from 3.87% in the German supply scenario to 7.46% in the Chinese supply scenario. The end-of-life phase is responsible for the same absolute value of the impact across all scenarios, given that it always takes place in Italy, and is responsible for a share of the impact ranging from 2.99% in the Chinese supply scenario to 4.80% in the Italian supply scenario. The installation is the phase accounting for the lowest impact in terms of GWP, being responsible for less than 0.90% of the total impact across all scenarios considered.

The numerical values of the GWP reported in Figure 55 fall within the ranges encountered in selected contributions from the literature. For example, they are included in the range of the GWP for systems based on CdTe technology provided in the review from Ludin et al. (78).

Figure 56 shows the results for the energy payback time.

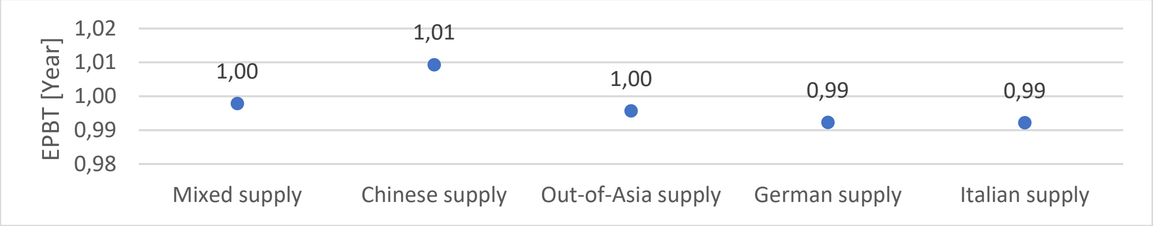

Figure 56: EPBT results for CdTe technology (Own production).

Figure 56 shows that the EPBT varies in a negligible manner across scenarios. It has been observed while analyzing Figure 54 that the cumulative energy demand grows 1.73% from the minimum value, corresponding to the Italian supply scenario, to the maximum value, corresponding to the Chinese supply scenario. Given that the location of installation and the yearly electricity production are the same across scenarios, the same result holds true for the EPBT. Namely, it changes 1.73% from the minimum of 0.99 years, corresponding to the Italian supply scenario, to the maximum of 1.01 years, corresponding to the Chinese supply scenario.
The numerical values obtained are in line with selected contributions from the literature. For example, they fall within the ranges of the EPBT for PV systems adopting CdTe technology indicated in the reviews from Peng et al. (85) and Ludin et al. (78).

Figure 57 shows the results for the CO_2 payback time.

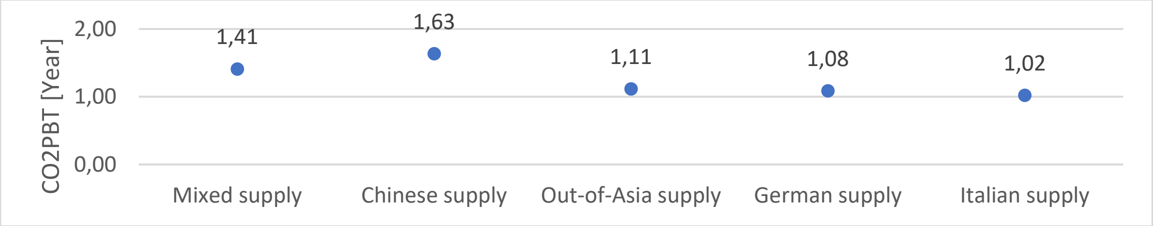

Figure 57: CO_2PBT results for CdTe technology (Own production).

Figure 57 shows that the CO_2PBT varies consistently across scenarios. As observed while analyzing Figure 55, the global warming potential grows 60.34% from the minimum value, represented by the Italian supply scenario, to the maximum value, represented by the Chinese supply scenario. It was observed that the main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country of modules manufacturing. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant.

Consequently, the same result observed for the GWP holds true for the CO_2PBT. Namely, it grows 60.34% from the minimum of 1.02 years, represented by the Italian supply scenario, to the maximum of 1.63 years, represented by the Chinese supply scenario. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is the grid carbon intensity of the country of modules manufacturing.

The results obtained are compared with findings from the literature. It is observed in the contribution from Mukisa et al. (105), analyzing systems based on multicrystalline technology, that for a fixed location of installation, the variation of the CO_2PBT can be mainly attributed to the grid carbon intensity of the country of modules manufacturing. The results obtained suggest that the observation from the mentioned scholars holds true also for systems based on CdTe technology.

5.3.6. OPV

Figure 58 shows the results for the cumulative energy demand.

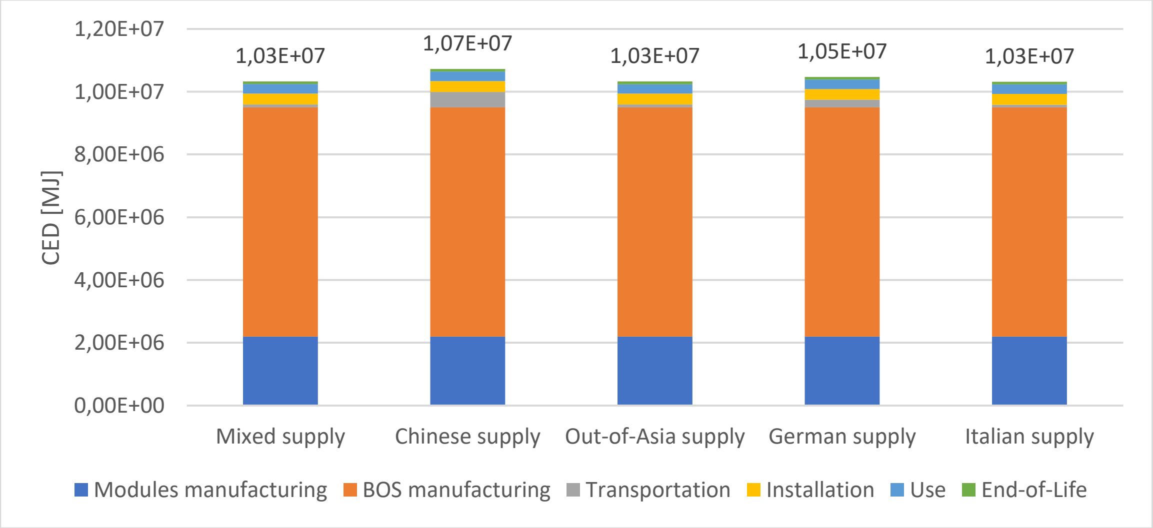

Figure 58: CED results for OPV technology (Own production).

Figure 58 shows a limited variability of the cumulative energy demand across the scenarios considered. The lowest value of the CED corresponds to the Italian supply scenario and is equal to 1.03*10^7 MJ, while the highest value corresponds to the Chinese supply scenario and is equal to 1.07*10^7 MJ. The maximum is only 3.96% higher than the minimum. The variation of the CED across scenarios is due to the different distances covered and shares of transport modes considered, impacting the transportation phase. For example, the transportation phase in the Chinese supply scenario is responsible for a CED more than five times higher than in the Italian supply scenario.

Considering the breakdown into phases, modules manufacturing phase accounts from 20.51% to 21.32% of the total CED depending on the scenario considered. The CED of the modules manufacturing phase is equal to 0.22*10^7 MJ across all scenarios. BOS manufacturing is the most impactful phase and is responsible for over 68.06% of the total CED across all scenarios. The fact that the BOS manufacturing is the most impactful phase is confirmed by results from scholars analyzing systems based on OPV technology, such as Tsang et al. (170). The remaining phases show values of the impact as a percentage with respect to the impact over the full life cycle in line with the ranges encountered in the literature analyzed and reported in Subsection 2.2.5. The installation phase accounts from 3.22% to 3.35% of the total CED depending on the scenario. The use phase accounts from 2.80% to 2.91% of the total impact depending on the scenario. The transportation phase is responsible for a share of the total CED ranging from 0.84% in the Italian supply scenario to 4.62% in the Chinese supply scenario. End-of-life is the phase accounting for the lowest impact, corresponding to less than 0.83% of the total CED across all scenarios.

The results obtained are compared with findings from the literature. First, it has been observed in Subsection 2.2.5 that the values of the impact of the transportation phase encountered in the sample analyzed are limited, accounting from 0.47% to 4.00% of the total CED over the life cycle except in one contribution indicating the value of 11.00%, as shown by Figure 28. Consequently, it is reasonable that varying the distances covered in the transportation phase has a limited impact on the total CED over the life cycle. Second, selected contributions from the literature, such as Serrano-Lujan et al. (102), assume the primary energy embedded in the modules manufacturing process to remain unchanged while varying the country of manufacturing.

Figure 59 shows the results for the global warming potential.

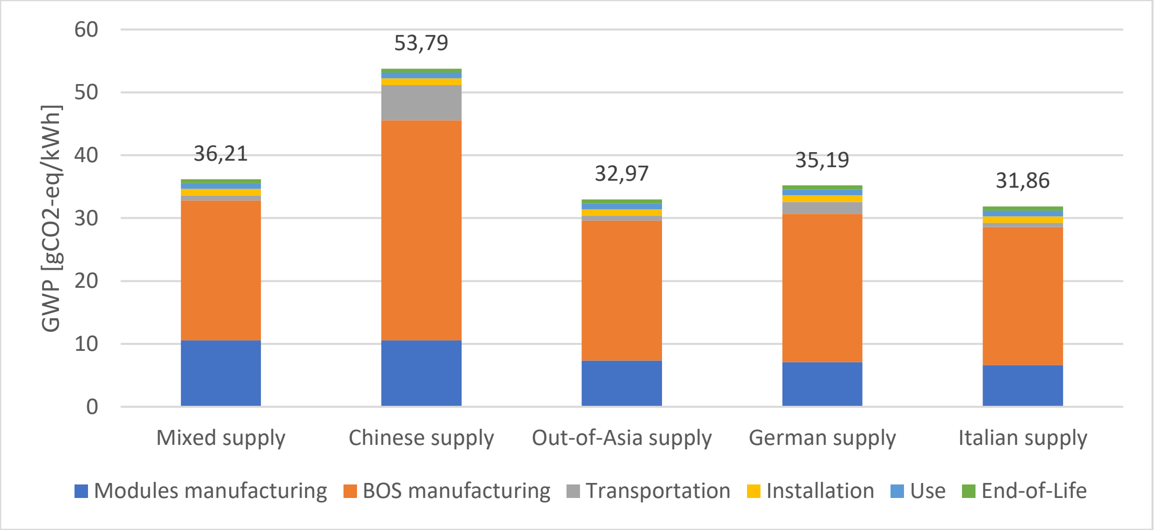

Figure 59: GWP results for OPV technology (Own production).

Figure 59 shows a consistent variation of the global warming potential across scenarios. The least polluting scenario is the Italian supply scenario, totaling 31.86 $gCO_{2\text{-eq}}$/kWh, while the Chinese supply is the most polluting scenario, emitting 68.81% more than the Italian supply scenario, namely 53.79 $gCO_{2\text{-eq}}$/kWh. The differences across scenarios are driven by the variation of the impact of the BOS manufacturing phase, responsible for over 61.44% of the impact across all scenarios. The variation of the impact of the BOS manufacturing phase across scenarios is driven by the different grid carbon intensities of the manufacturing countries. For example, BOS manufacturing accounts for 35.03 $gCO_{2\text{-eq}}$/kWh in the Chinese supply scenario and for 21.96 $gCO_{2\text{-eq}}$/kWh in the Italian supply scenario. This result is in line with Muller et al. (74), where it is observed that the carbon footprint of BOS components more than double when the electricity mix used in the production process changes from the European to the Chinese one.

Considering the breakdown into phases, BOS manufacturing is the most impactful phase, responsible for over 61.44% of the total GWP across all scenarios. Modules manufacturing is the second most impactful phase, accounting from 19.62% of the total impact in the Chinese supply scenario to 29.15% in the Mixed supply scenario. The transportation phase is responsible for a share of the total GWP ranging from 2.16% in the Italian supply scenario to 10.42% in the Chinese supply scenario. The installation phase accounts from 1.93% of the total GWP in the Chinese supply scenario to 3.26% in the Italian supply scenario. The use phase is responsible for a share of the total impact ranging from 1.68% in the Chinese supply scenario to 2.83% in the Italian supply scenario. The end-of-life is the phase responsible for the lowest impact in terms of GWP, corresponding to less than 2.07% of the total impact across all scenarios.

Figure 60 shows the results for the energy payback time.

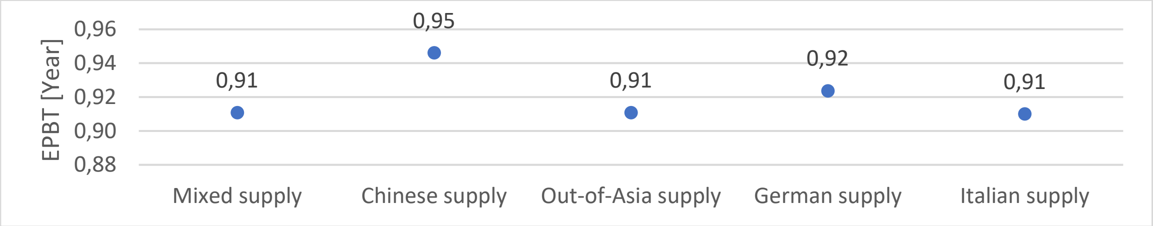

Figure 60: EPBT results for OPV technology (Own production).

Figure 60 shows that the EPBT varies in a negligible manner across scenarios. It has been observed while analyzing Figure 58 that the cumulative energy demand grows 3.96% from the minimum value, corresponding to the Italian supply scenario, to the maximum value, corresponding to the Chinese supply scenario. Given that the location of installation and the yearly electricity production are fixed across scenarios, the same result holds true for the EPBT. Namely, it changes 3.96% from the minimum of 0.91 years, corresponding to the Italian supply scenario, to the maximum of 0.95 years, corresponding to the Chinese supply scenario.

Figure 61 shows the results for the CO_2 payback time.

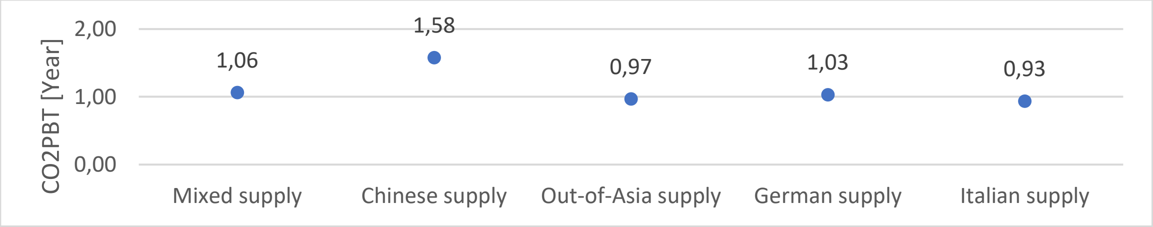

Figure 61: CO_2PBT results for OPV technology (Own production).

Figure 61 shows that the CO_2PBT varies consistently across scenarios. As observed while analyzing Figure 59, the global warming potential grows 68.81% from the minimum value, represented by the Italian supply scenario, to the maximum value, represented by the Chinese supply scenario. It was observed that the main driver of the variation of the GWP across scenarios is represented by the grid carbon intensities of the countries of BOS manufacturing. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant. Consequently, the same result observed for the GWP holds true for the CO_2PBT. Namely, it grows 68.81% from the minimum of 0.93 years, represented by the Italian supply scenario, to the maximum of 1.58 years, represented by the Chinese supply scenario. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is represented by the grid carbon intensities of the countries of BOS manufacturing.

5.3.7. Comparisons of results

In the current subsection, the results obtained are compared across scenarios and technologies.

5.3.7.1. Comparisons of results: cumulative energy demand

Figure 62 shows the comparisons of the cumulative energy demand of the different scenarios over the technologies considered.

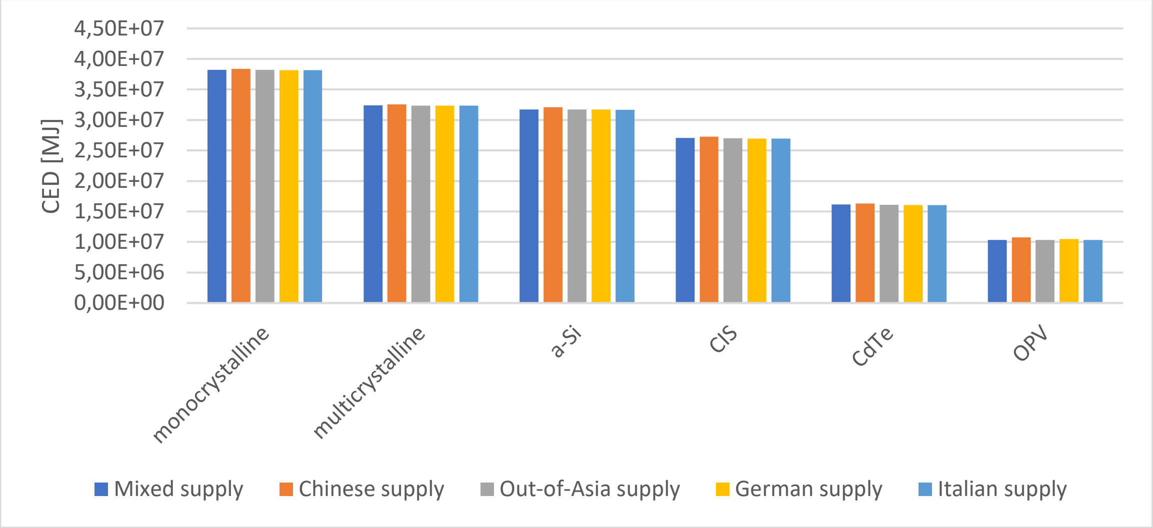

Figure 62: Comparisons of CED results of scenarios over the technologies (Own production).

Figure 62 shows that, considering a fixed technology, the variation of the cumulative energy demand across scenarios is limited. The variation from the minimum value to the maximum value of the CED ranges from 0.59% for monocrystalline technology to 3.96% for OPV technology. For example, considering the monocrystalline technology, the CED grows 0.59% from the minimum of 3.82*10^7 MJ, corresponding to the Italian supply scenario, to the maximum of 3.84*10^7 MJ, corresponding to the Chinese supply scenario. As mentioned in the previous subsections presenting results for each single technology, the variation of the CED across scenarios while considering a fixed technology is due to the different distances and share of transport modes considered, impacting the transportation as well as the use phase, in case of the inverter replacement. Furthermore, it is observed that for all technologies, the most impactful scenario is the Chinese supply. On the other hand, the least impactful scenario is the Italian supply for all technologies, except for CIS, where the least impactful scenario is the German supply.

Figure 63 shows the comparisons of the cumulative energy demand of the different technologies over the scenarios considered.

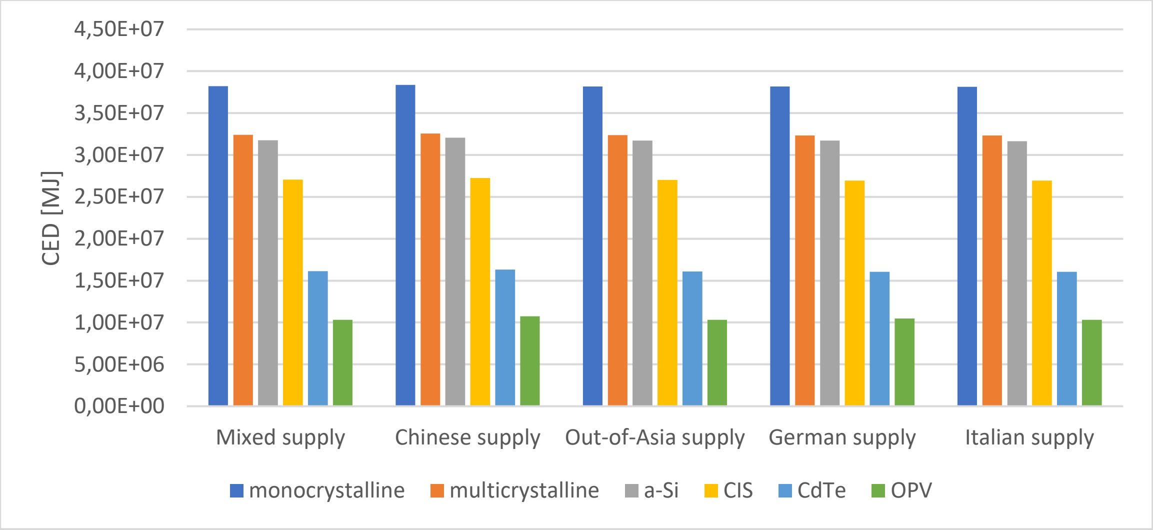

Figure 63: Comparisons of CED results of technologies over the scenarios (Own production).

Figure 63 shows that, while considering a fixed scenario, the variation of the cumulative energy demand across technologies is considerable. For all scenarios, the CED grows more than 3.58 times from the least impactful technology to the most impactful one. For example, considering the Mixed supply scenario, the CED ranges from a minimum of 1.0*10^7 MJ for OPV technology and grows 3.70 times up to the maximum of 3.8*10^7 MJ for monocrystalline technology. Furthermore, for all scenarios it is observed the same ranking of technologies from the highest to the lowest CED: monocrystalline, multicrystalline, a-Si, CIS, CdTe, OPV. The higher CED of first-generation technologies is driven by the energy intensive module manufacturing process: in Subsections 5.3.1 and 5.3.2 it has been observed that the modules manufacturing phase accounts for over 80% of the total CED across all scenarios. The lower CED of the OPV technology is driven by the lower energy requirements of the modules manufacturing process compared to the other technologies. In the evaluation framework developed, the cumulative energy demand for the manufacturing of OPV modules is equal to 110 MJ/m^2 and it is one order of magnitude lower if compared to the cumulative energy demands of the other technologies, as can be observed by looking at Table 6 in Chapter 4.

The ranking of technologies depending on the CED presented above is in line with selected contributions from the literature. For example, Laleman et al. (60) show the same ranking of technologies as the one presented above, with the exception that OPV technology is not considered by the mentioned scholars.

5.3.7.2. Comparisons of results: global warming potential

Figure 64 shows the comparisons of the global warming potential of the different scenarios over the technologies considered.

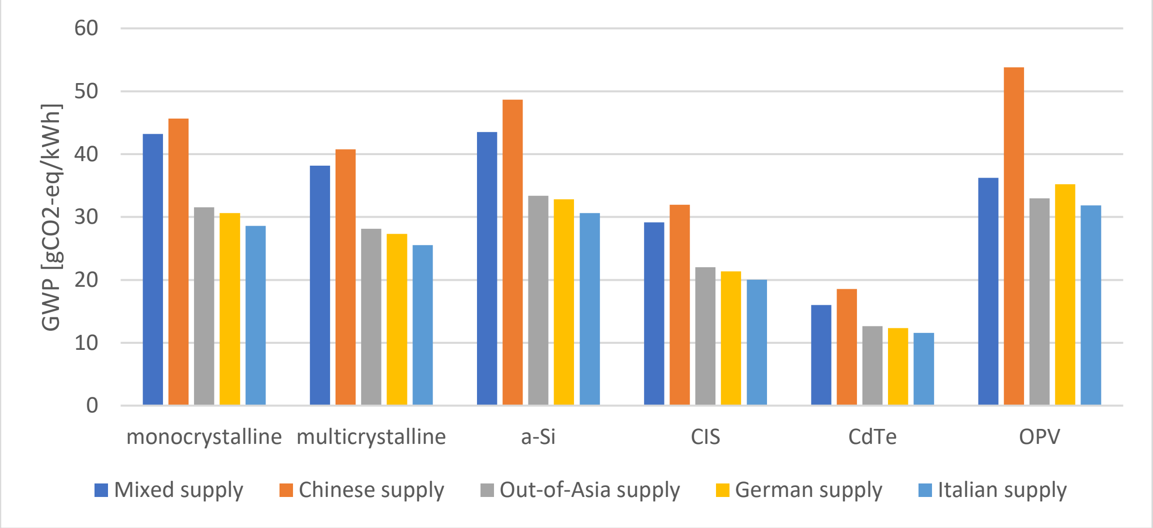

Figure 64: Comparisons of GWP results of scenarios over the technologies (Own production).

Figure 64 shows that, considering a fixed technology, the variation of the global warming potential across scenarios is considerable. For all technologies, the GWP grows more than 58.85% from the minimum value, corresponding to the Italian supply scenario, to the maximum value, corresponding to the Chinese supply scenario. For example, considering the monocrystalline technology, the GWP grows 59.75% from the minimum of 28.57 $gCO_{2\text{-eq}}$/kWh, corresponding to the Italian supply scenario, to the maximum of 45.64 $gCO_{2\text{-eq}}$/kWh, corresponding to the Chinese supply scenario. Furthermore, for all technologies except OPV, the ranking from the most polluting to the least polluting scenario is the following: Chinese supply, Mixed supply, Out-of-Asia supply, German supply, Italian supply. As mentioned in the previous subsections presenting results for each single technology, the main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country of modules manufacturing for first- and second-generation technologies, while for OPV technology it was observed that the main driver of the variation of the GWP across scenarios is represented by the grid carbon intensities of the countries where BOS components are manufactured.

Figure 65 shows the comparisons of the global warming potential of the different technologies over the scenarios considered.

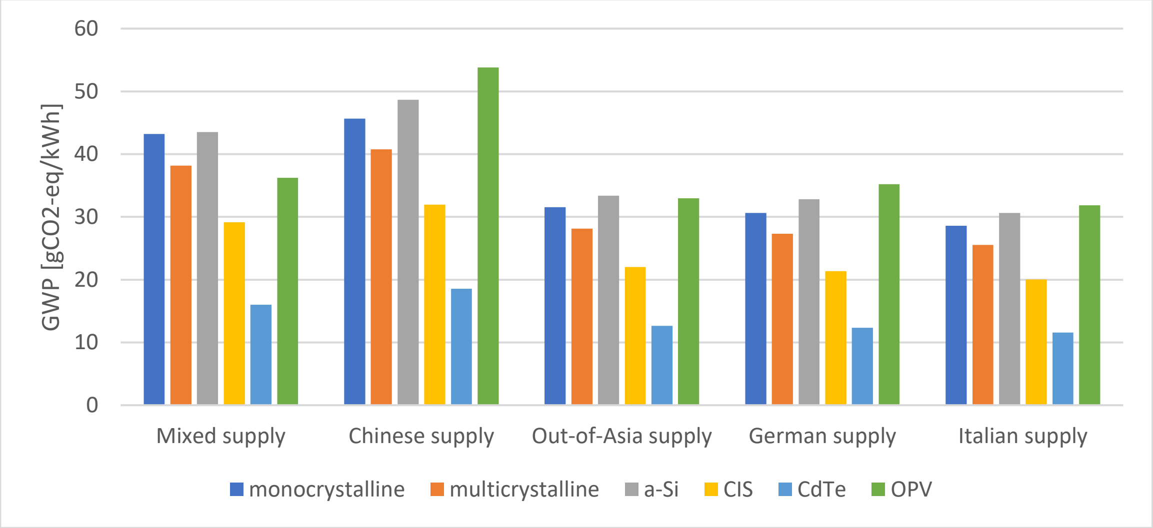

Figure 65: Comparisons of GWP results of technologies over the scenarios (Own production).

Figure 65 shows that, while considering a fixed scenario, the variation of the global warming potential across technologies is considerable. For all scenarios, the GWP grows more than 2.64 times from the least polluting technology to the most polluting one. Taking the Mixed supply scenario as an example, the GWP grows 2.72 times from the minimum value of 16.00 $gCO_{2\text{-eq}}$/kWh for CdTe technology to the maximum value of 43.53 $gCO_{2\text{-eq}}$/kWh for a-Si technology. It is observed that in all scenarios except the Mixed supply and the Out-of-Asia supply, the ranking of technologies from the highest to the lowest GWP is the following: OPV, a-Si, monocrystalline, multicrystalline, CIS, CdTe. Furthermore, it is detected that in all scenarios the least polluting technology is CdTe. The higher GWP of the OPV technology is driven by its limited energy production compared to the other technologies. It is computed from the evaluation framework that the OPV technology produces from 3.15 to 4.28 times less energy over the lifetime compared to the other technologies. The lower GWP of the CdTe technology is driven by the lower $CO_{2\text{-eq}}$ emissions over the life cycle compared to the other first and second-generation technologies and by the energy production comparable to the other first and second-generation technologies. For example, it is computed from the evaluation framework that a system based on CdTe technology releases from 39.65% to 43.00% less $CO_{2\text{-eq}}$ emissions over the life cycle depending on the scenarios, while generating 3.87% more energy over the lifetime, if compared to the CIS technology, representing the technology with the second lowest GWP across all scenarios.

The results obtained are compared with contributions from the literature. For example, it is found the same ranking of technologies from the highest to the lowest GWP proposed above in the review from Peng et al. (85), excluding OPV technology since not included by the mentioned scholars and with the exception that monocrystalline technology features a higher GWP than a-Si technology in the ranking indicated by the mentioned scholars.

5.3.7.3. Comparisons of results: energy payback time

Figure 66 shows the comparisons of the energy payback time of the different scenarios over the technologies considered.

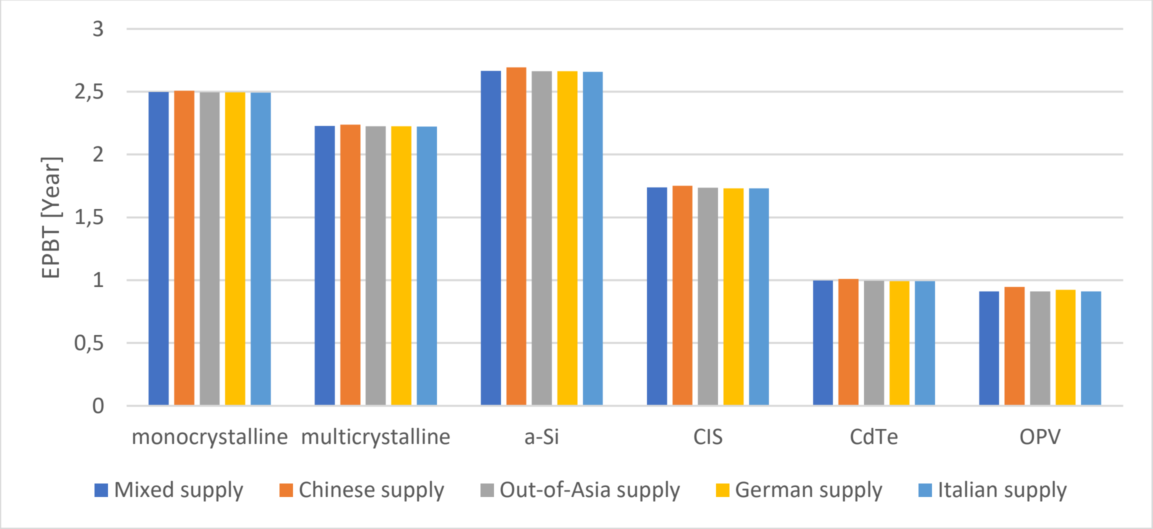

Figure 66: Comparisons of EPBT results of scenarios over the technologies (Own production).

Figure 66 shows that, considering a fixed technology, the variation of the EPBT across scenarios is limited. For example, considering the monocrystalline technology, the EPBT ranges from 2.49 years in the Italian supply scenario to 2.51 years in the Chinese supply scenario. As a matter of fact, it has been observed while analyzing Figure 62 that, considering a fixed technology, the variation of the cumulative energy demand across scenarios is limited. Given that the location of installation and the yearly electricity production for a given technology are fixed across scenarios, the same patterns observed for the CED hold true for the EPBT. First, considering a fixed technology the variation from the minimum to the maximum EPBT across scenarios is limited and ranges from 0.59% for monocrystalline technology to 3.96% for OPV technology. Second, for all technologies the scenario with the highest EPBT is the Chinese supply, since it is the scenario characterized by the highest CED. Third, for all technologies except CIS, the scenario with the lowest EPBT is the Italian supply. The result is due to the fact that the Italian supply is the scenario characterized by the lowest CED for all technologies except CIS.

Figure 67 shows the comparison of the energy payback time of the different technologies over the scenarios considered.

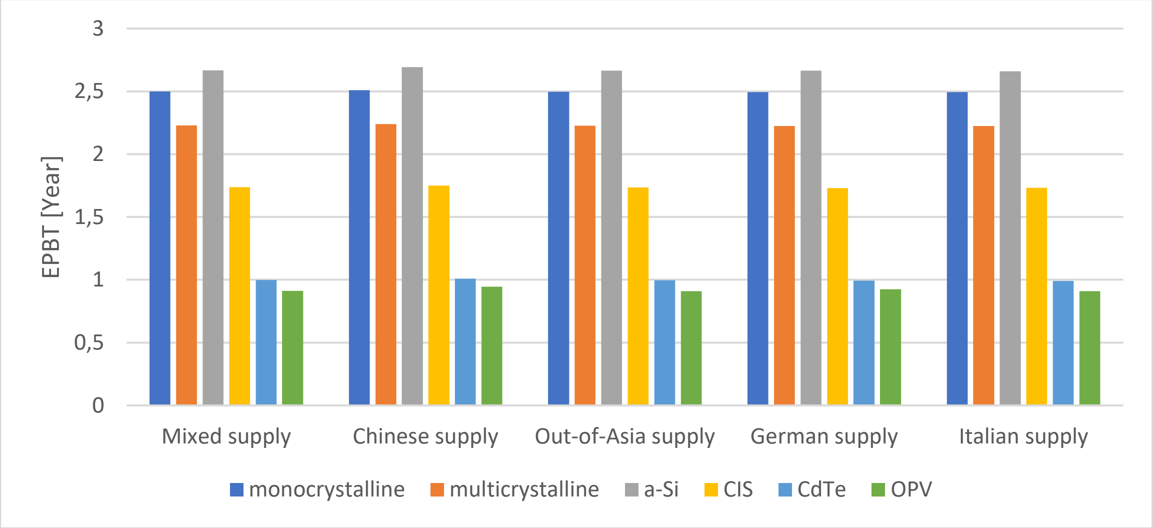

Figure 67: Comparisons of EPBT results of technologies over the scenarios (Own production).

Figure 67 shows that, considering a fixed scenario, the variation of the EPBT across technologies is considerable. For all scenarios, the EPBT grows more than 2.85 times from the lowest to the highest value. For example, considering the Mixed supply scenario, the EPBT grows 2.93 times from the minimum of 0.91 years for OPV technology to the maximum of 2.67 years for a-Si technology. Furthermore, for all scenarios it is observed the same ranking of technologies from the highest to the lowest EPBT: a-Si, monocrystalline, multicrystalline, CIS, CdTe, OPV. The higher EPBT of the a-Si technology is explained by the lower energy produced over the lifetime compared to the other first and second-generation technologies. For example, it is computed from the evaluation framework that the energy produced over the lifetime by the a-Si technology is 22.19% lower compared to the monocrystalline technology. OPV ranks as the best technology in terms of EPBT in particular because of the lower energy requirements over the life cycle with respect to the other technologies. For example, the OPV technology has a cumulative energy demand over the life cycle from 72.05% to 72.98 % lower depending on the scenario, if compared to the monocrystalline technology.

The results obtained are in line with selected contributions from the literature. For example, in the review from Peng et al. (85) it is found the same ranking of technologies from the highest to the lowest EPBT proposed above, with the exception that OPV is not included by the mentioned scholars.

5.3.7.4. Comparisons of results: CO_2 payback time

Figure 68 shows the comparisons of the CO_2 payback time of the different scenarios over the technologies considered.

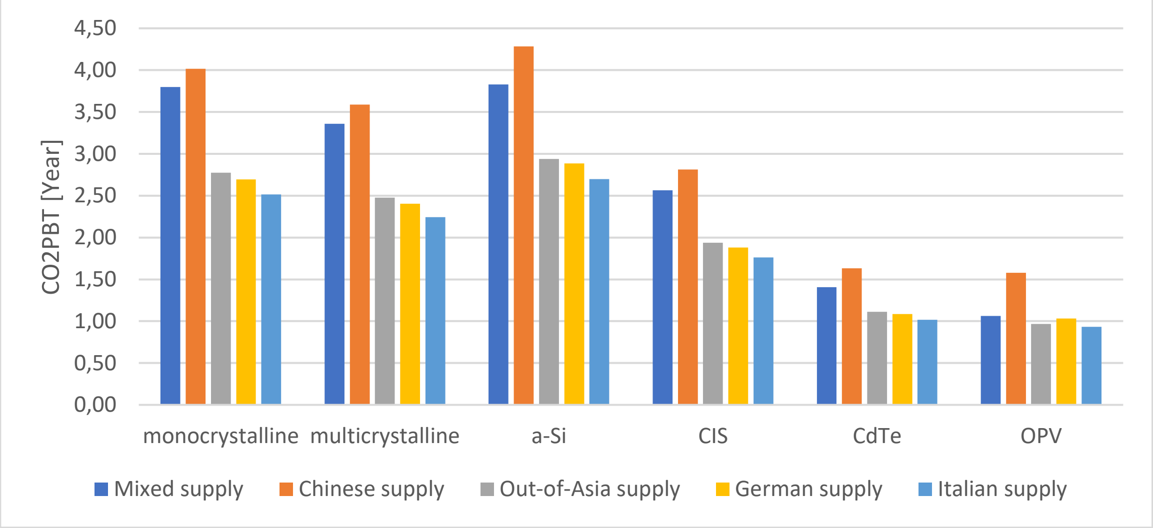

Figure 68: Comparisons of CO_2PBT results of scenarios over the technologies (Own production).

Figure 68 shows that, considering a fixed technology, the variation of the CO_2PBT across scenarios is considerable. For example, considering the monocrystalline technology, the CO_2PBT grows 59.75% from the lowest value of 2.51 years for the Italian supply scenario to the highest value of 4.02 years for the Chinese supply scenario. It has been observed while analyzing Figure 64 that, for a fixed technology, the variation of the global warming potential across scenarios is considerable. Given that the location of installation and the electricity produced are fixed across scenarios, the yearly emissions displaced are constant. Consequently, the same results observed for the GWP hold true for the CO_2PBT. First, for all technologies, the CO_2PBT grows more than 58.85% from the lowest value, represented by the Italian supply scenario, to the highest value, represented by the Chinese supply scenario. Second, for all technologies except OPV, the ranking of scenarios from the highest to the lowest CO_2PBT is the following: Chinese supply, Mixed supply, Out-of-Asia supply, German supply, Italian supply. As observed for the GWP, the main driver of the variation of the CO_2PBT across scenarios is represented by the grid carbon intensity of the country of modules manufacturing for first- and second-generation technologies, and by the grid carbon intensities of the countries where BOS components are manufactured for OPV technology.

Figure 69 shows the comparison of the CO_2 payback time of the different technologies over the scenarios considered.

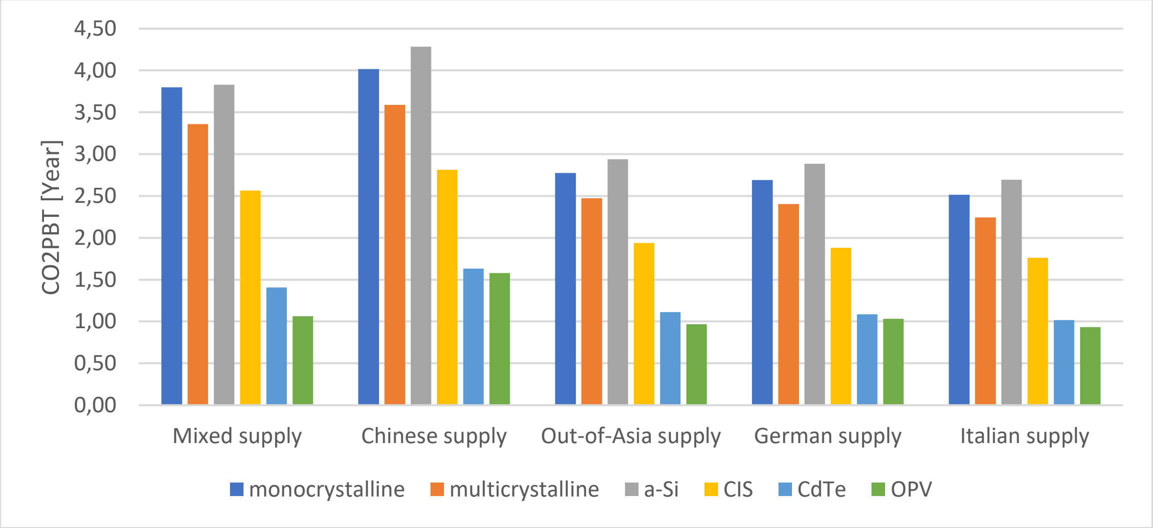

Figure 69: Comparisons of CO_2PBT results of technologies over the scenarios (Own production).

Figure 69 shows that, considering a fixed scenario, the variation of the CO_2PBT across technologies is considerable. For all scenarios, the CO_2PBT grows more than 2.72 times from the lowest to the highest value. For example, considering the Mixed supply scenario, the CO_2PBT grows 3.61 times from the minimum of 1.06 years for OPV technology to the maximum of 3.83 years for a-Si technology. Furthermore, it is observed that for all scenarios the ranking of technologies from the highest to the lowest CO_2PBT is the following: a-Si, monocrystalline, multicrystalline, CIS, CdTE, OPV. The higher CO_2PBT of the a-Si technology is driven by the lower energy production over the lifetime compared to the other first- and second-generation technologies. For example, it is computed from the evaluation framework that the energy produced over the lifetime by the a-Si technology is 22.19% lower if compared to the monocrystalline technology. The lower CO_2PBT of the OPV technology is justified by the lower $CO_{2\text{-eq}}$ emissions over the life cycle compared to first- and second-generation technologies. For example, it is computed from the evaluation framework that the OPV technology releases from 70.88% to 79.29% less $CO_{2\text{-eq}}$ emissions over the life cycle compared to the monocrystalline technology.

5.4. Sensitivity analysis

The current section presents the sensitivity analyses on a selection of parameters. Parameters are selected based on their influence on results and on the likelihood of their variation with respect to their values in the scenarios analyzed in the previous

Section 5.3.

The first parameter included in the sensitivity analysis is the irradiation. The irradiation is a fundamental factor in defining the energy produced by the PV system over its lifetime. As demonstrated in the literature review chapter, it represents the parameter most often subject to sensitivity analyses in the literature analyzed. As a matter of fact, the irradiation changes significantly depending on the location considered. For example, in Italy the irradiation spans from 1050 kWh/(m^2*year) to over 1800 kWh/(m^2*year) (234).

The second parameter included in the sensitivity analysis is the modules conversion efficiency. The literature review presented the wide ranges of values encountered in the sample analyzed for the modules conversion efficiency of the different technologies considered, as well as the common inclusion of modules conversion efficiency in sensitivity analyses.

A last analysis is proposed by including the benefits from the end-of-life phase. In Paragraph 2.2.5.7 it was observed that multiple authors consider the benefits from the end-of-life as a credit for the system under analysis. Furthermore, the topic of recycling is considered important for the future sustainability of PV technologies (98), since it can improve their environmental and economic performances (23).

All sensitivity analyses are completed on the Mixed supply scenario, also indicated as the reference scenario in Section 5.2. The values of the input variables for the evaluation framework applied in the Mixed supply scenario are recapitulated in Table 18.

Input variables		
Capacity of PV system	[MW]	1
Country of installation	[-]	Italy
Country of modules manufacturing	[-]	China
Modules distance road	[km]	696
Modules distance water	[km]	15537
Inverter country of manufacturing	[-]	Germany
Inverter distance road	[km]	836
Inverter distance water	[km]	0
BOS (except inverter) country of manufacturing	[-]	Italy
BOS (except inverter) distance road	[km]	300
BOS (except inverter) distance water	[km]	0
End-of-life benefits	[-]	No

Table 18: Mixed supply scenario’s input variables (Own production).

Now that the sensitivity analyses have been introduced, the following subsection will present in detail the sensitivity analysis on the irradiation.

5.4.1. Irradiation

The value of the irradiation in Italy applied in the Mixed supply scenario is equal to 1486 kWh/(m^2*year) (167). Nevertheless, a significant variation of the irradiation is observed within the country. Data from the ENEA[6] show that the irradiation in Italy ranges from a minimum of 1050 kWh/(m^2*year) in Livigno, to a maximum of 1815 in Lampedusa (234). Thus, it is decided to include in the sensitivity analysis a variation of the irradiation of -30% (1040 kWh/(m^2*year)) and +30% (1932 kWh/(m^2*year)) with respect to the value of 1486 kWh/(m^2*year) applied in the reference scenario. The results of the sensitivity analysis will now be provided for each of the four impact indicators.

The first impact indicator, the cumulative energy demand, is not impacted by a variation of the irradiation, as shown by Figure 70.

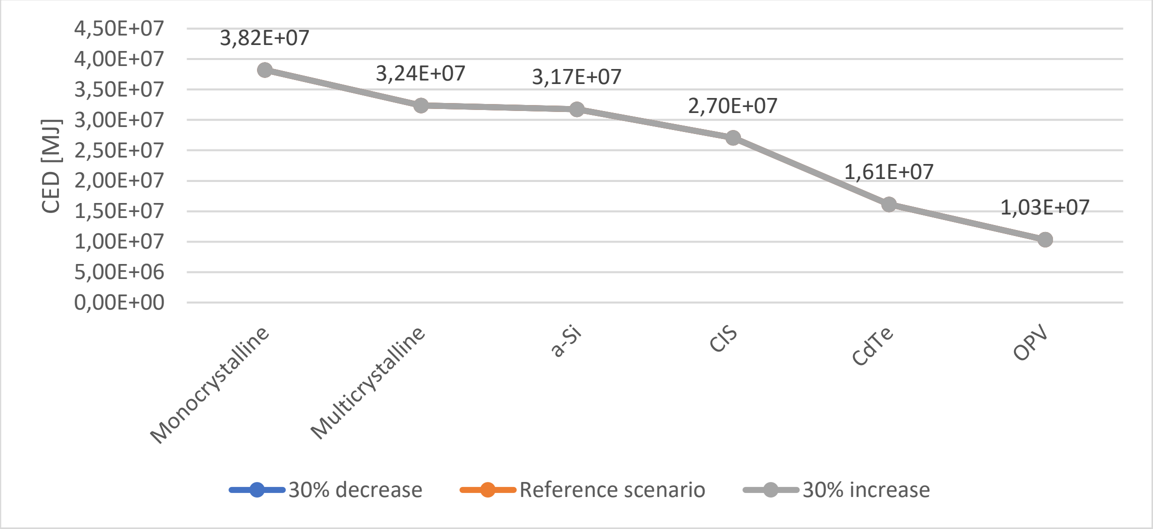

Figure 70: Sensitivity analysis of the CED with respect to irradiation (Own production).

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[6] ENEA: Italian National Agency for New Technologies, Energy and Sustainable Economic Development

The results for the second impact indicator, the global warming potential, are provided in Figure 71.

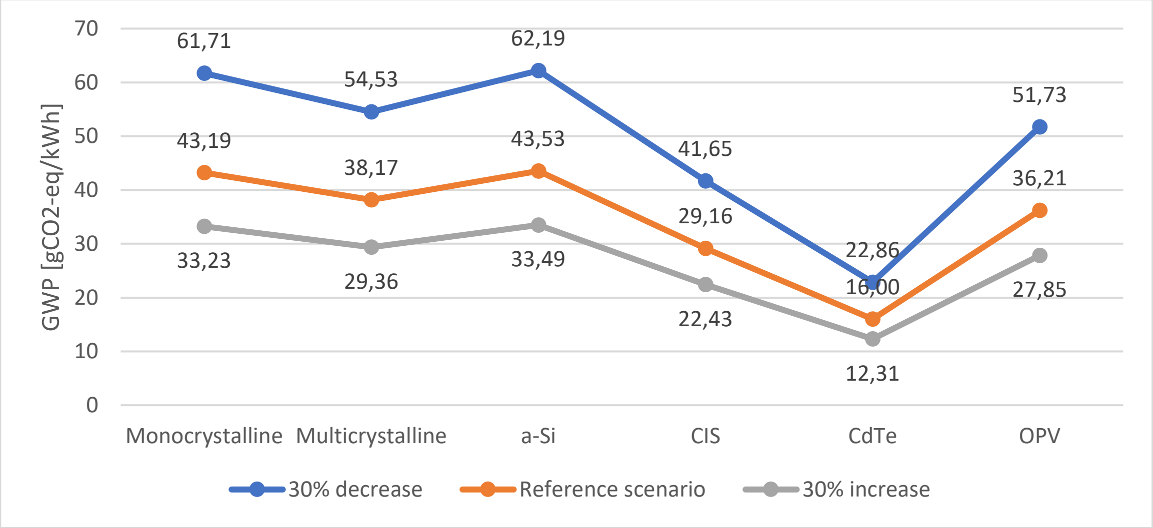

Figure 71: Sensitivity analysis of the GWP with respect to irradiation (Own production).

Figure 71 shows the significant impact of the irradiation on the global warming potential. For all technologies considered, increasing the irradiation by 30% with respect to the value in the reference scenario brings to a reduction of 23.08% of the GWP. As a matter of fact, the denominator of the GWP is the electricity generated during lifetime and it grows by 30%, while the numerator is represented by the $CO_{2\text{-eq}}$ emissions over the life cycle and it remains unchanged. Consequently, the GWP decreases by 23.08%. Conversely, decreasing the irradiation by 30% with respect to the value in the reference scenario brings to an increase of 42.86% of the GWP across all the technologies considered. The mathematical explanation is given by the fact that decreasing the irradiation by 30% induces a reduction of the same percentage of the denominator of the GWP, so that the GWP grows by 42.86%.

The results obtained are in line with selected contributions from the literature. For example, Nordin et al. (83) observe that the increase in irradiation reduces the global warming potential. Furthermore, the significant impact of the irradiation on the GWP is confirmed by looking at results from Rahman et al. (36), where it is shown that a 20% increase of the irradiation brings to a 16.67% decrease of the GWP.

The results for the third impact indicator, the energy payback time, are provided in Figure 72.

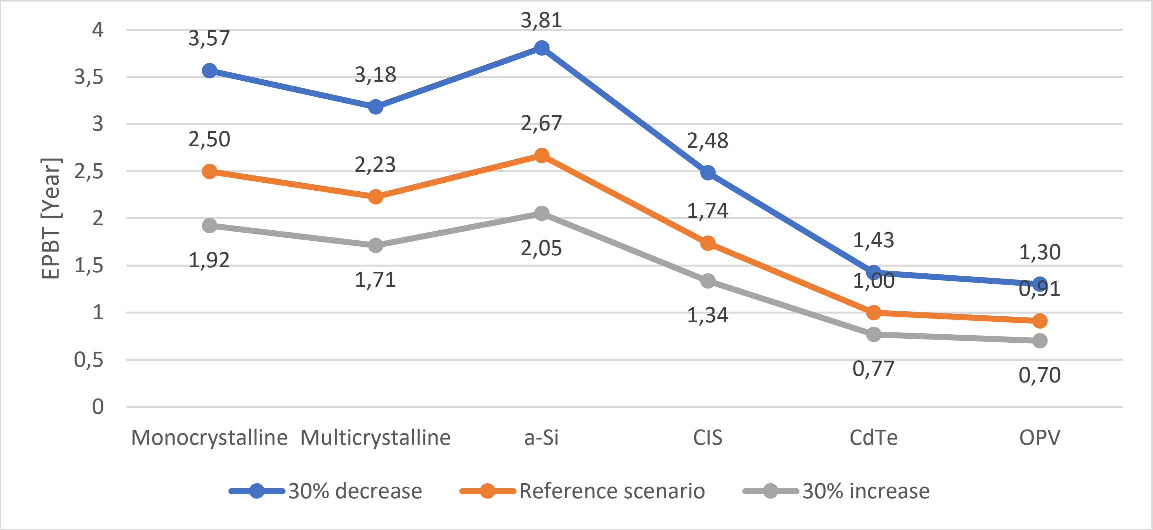

Figure 72: Sensitivity analysis of the EPBT with respect to irradiation (Own production).

Figure 72 shows the significant impact of the irradiation on the EPBT. For all technologies, increasing the irradiation by 30% with respect to the value in the reference scenario brings to a reduction of 23.08% of the EPBT. As a matter of fact, the numerator of the EPBT is the cumulative energy demand over the life cycle and it remains unchanged, while the denominator is the yearly energy production and it grows 30%. Consequently, the EPBT is reduced by 23.08%. Conversely, decreasing by 30% the irradiation with respect to the value in the reference scenario brings to a 42.86% increase of the EPBT across all technologies considered. The mathematical explanation is given by the fact that decreasing the irradiation by 30% induces a reduction of the same percentage of the denominator of the EPBT, so that the EPBT grows by 42.86%.

The results obtained are in line with selected contributions from the literature. Sumper et al. (150) mention the strong decrease in the EPBT while the irradiation increases. Furthermore, the strong impact of the irradiation on the EPBT is confirmed by looking at results from Nordin et al. (83), where it is shown that a 75% increase of the irradiation brings to 42.86% decrease of the EPBT.

Figure 73 provides the results for the fourth impact indicators, the CO_2 payback time.

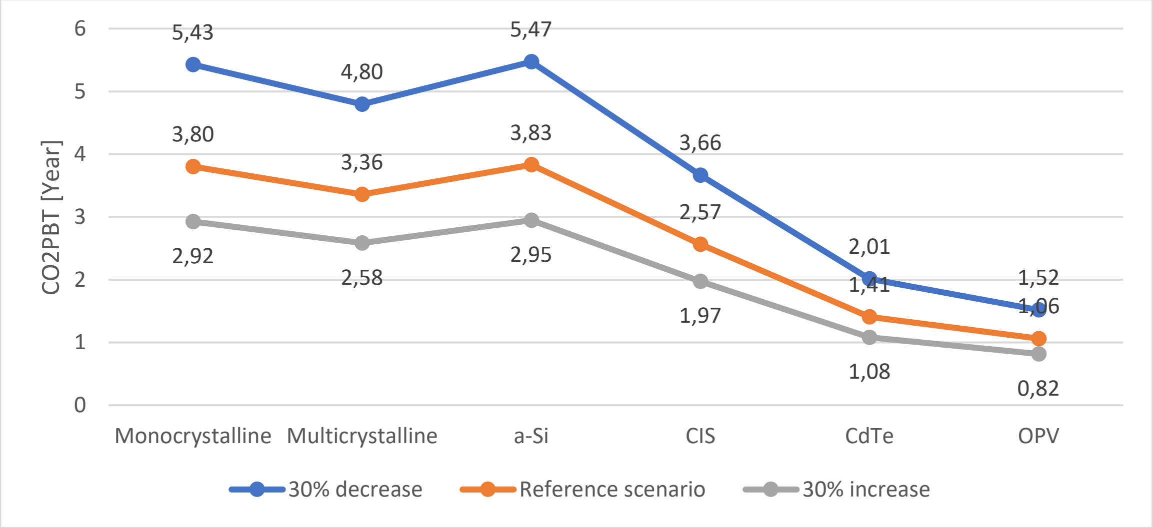

Figure 73: Sensitivity analysis of the CO_2PBT with respect to irradiation (Own production).

Figure 73 shows that the variation of the irradiation has a significant impact on the CO_2PBT. For all technologies, increasing the irradiation by 30% with respect to the value in the reference scenario brings to a reduction of 23.08% of the CO_2PBT. The mathematical explanation is given by the fact that the numerator of the CO_2PBT is represented by the $CO_{2\text{-eq}}$ emissions over the life cycle and it remains unchanged, while the denominator is represented by the yearly $CO_{2\text{-eq}}$ emissions avoided and it grows by 30%. The consequence is a reduction of 23.08% of the CO_2PBT. Conversely, a reduction of 30% of the irradiation with respect to the value in the reference scenario brings to a 42.86% increase of the CO_2PBT for all technologies. This is explained by the fact that the yearly $CO_{2\text{-eq}}$ emissions avoided decrease by 30% because of the decrease in the irradiation, so that the CO_2PBT grows by 42.86%.

The results obtained are in line with selected contributions from the literature. Nordin et al. (83) mention that the increase in irradiation reduces the CO_2PBT. Furthermore, the results provided by the mentioned scholars confirm the relevant impact of the irradiation on the CO_2PBT: it is shown in the cited paper that a 75% increase of the irradiation brings to a 42.31% decrease of the CO_2PBT (83).

5.4.2. Modules conversion efficiency

Paragraph 2.2.4.1 presented the wide ranges of values encountered in the sample analyzed for the modules efficiency of the technologies scrutinized. For example, considering the multicrystalline technology, the values of the modules conversion efficiency encountered in the literature and plotted in Figure 24 range from 12.5%

to 19.9%. The variation with respect to the value of 18% applied in the reference scenario corresponds to a 30.56% decrease and a 10.56% increase, respectively. Consequently, it is decided to consider in the current sensitivity analysis a wide variation of the modules conversion efficiency, ranging from -30% to +30% with respect to the values applied in the reference scenario. The modules conversion efficiencies applied in the reference scenario are recapitulated in Table 19.

Technology	Modules conversion efficiency [%]
Monocrystalline	19.5
Multicrystalline	18
CdTe	18
CIS	16
a-Si	7.5
OPV	5

Table 19: Modules conversion efficiencies in the reference scenario (Own production).

The results of the sensitivity analysis will now be provided for each of the four impact indicators.

The cumulative energy demand is not impacted by a variation of the modules conversion efficiency, as can be observed in Figure 74.

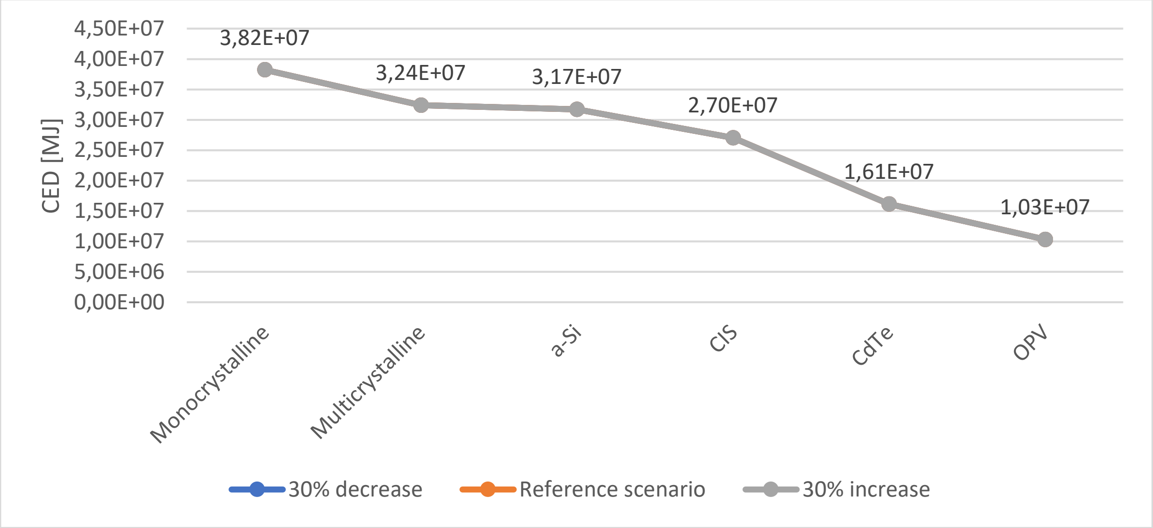

Figure 74: Sensitivity analysis of the CED with respect to modules conversion efficiency (Own production).

The results for the second impact indicator, the global warming potential, are provided in Figure 75.

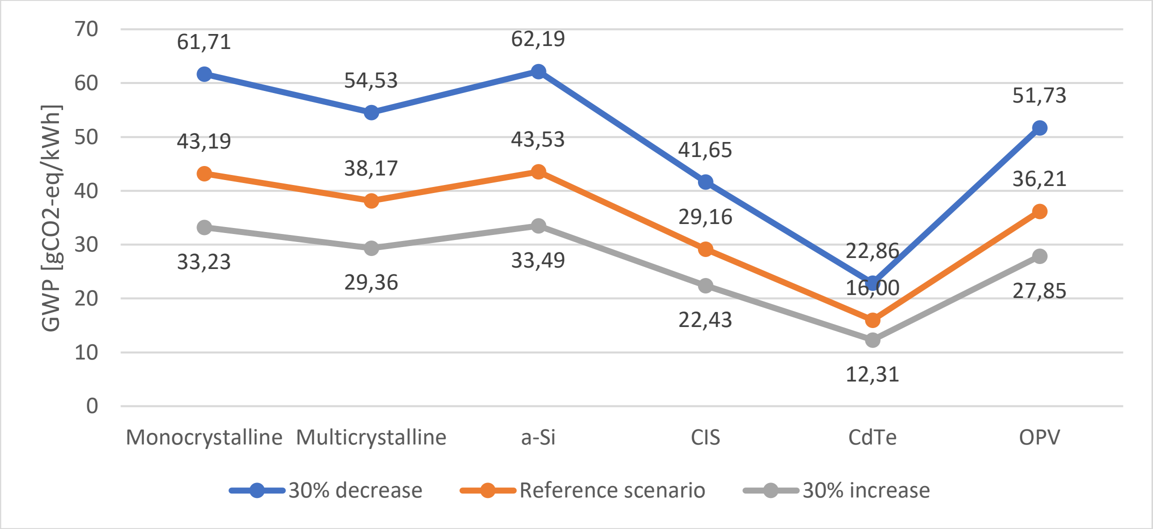

Figure 75: Sensitivity analysis of the GWP with respect to modules conversion efficiency (Own production).

Figure 75 demonstrates the significant impact of the modules conversion efficiency on the global warming potential. For all technologies, a 30% growth of the conversion efficiency with respect to the value in the reference scenario causes a reduction of 23.08% of the GWP. As a matter of fact, the denominator of the GWP is the electricity generated over the lifetime and it grows by 30%, while the numerator

is represented by the $CO_{2\text{-eq}}$ emissions during the life cycle and it remains unchanged. Consequently, the GWP decreases by 23.08%. Conversely, decreasing by 30% the modules conversion efficiency with respect to the value in the reference scenario causes a 42.86% increase of the GWP across all the technologies considered. The mathematical reason is given by the fact that decreasing by 30% the modules conversion efficiency brings to a reduction of the same percentage of the denominator of the GWP, so that the GWP grows by 42.86%.
The strong impact of the modules conversion efficiency on the GWP is confirmed by selected contributions from the literature. For example, it is shown in the paper from Rahman et al. (36) that increasing the modules conversion efficiency by 20% brings to a decrease of over 13.50% of the GWP.

The results for the energy payback time are provided in Figure 76.

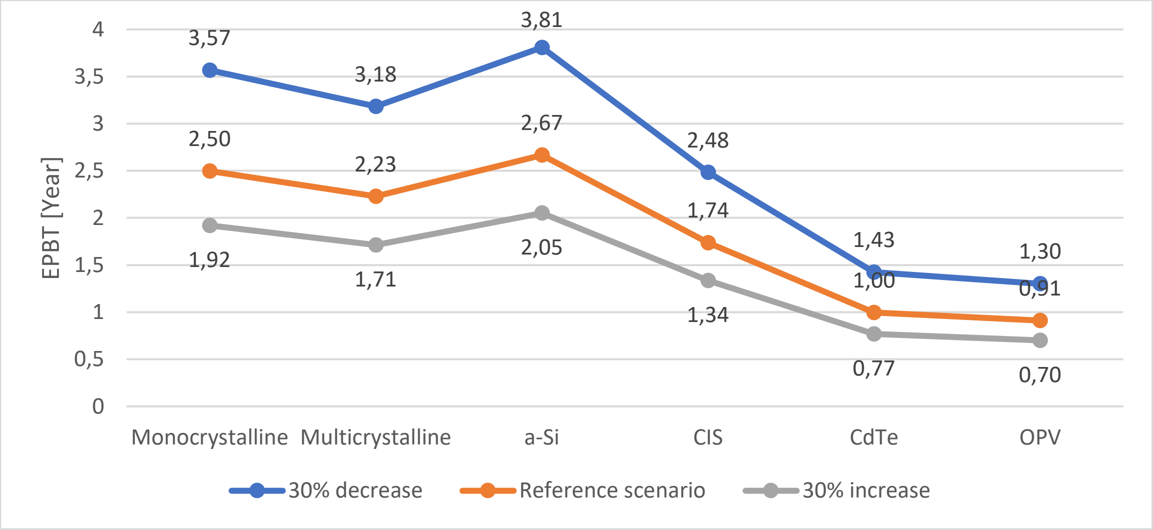

Figure 76: Sensitivity analysis of the EPBT with respect to modules conversion efficiency (Own production).

Figure 76 shows that the modules conversion efficiency has a significant impact on the EPBT. For all technologies, increasing the modules conversion efficiency by 30% with respect to the value in the reference scenario brings to a reduction of 23.08% of the EPBT. As a matter of fact, the numerator of the EPBT is the cumulative energy demand over the life cycle and it remains unchanged, while the denominator is the yearly energy production and it grows 30%. Consequently, the EPBT decreases by 23.08%. Conversely, decreasing the modules conversion efficiency by 30% with respect to the value in the reference scenario brings to an increase of 42.86% of the EPBT across all technologies considered. The mathematical explanation is given by the fact that decreasing the modules conversion efficiency by 30% brings to a reduction of the same percentage of the denominator of the EPBT, so that the EPBT grows by 42.86%.

The strong influence of the modules conversion efficiency on the EPBT is confirmed by selected contributions from the literature. For example, Vellini et al. (103) observe that in case of a percentage increase of modules conversion efficiency, the corresponding percentage reduction of the EPBT is equal to half the increase of the modules conversion efficiency.

The results for the fourth impact indicator, the CO_2 payback time, are provided in Figure 77.

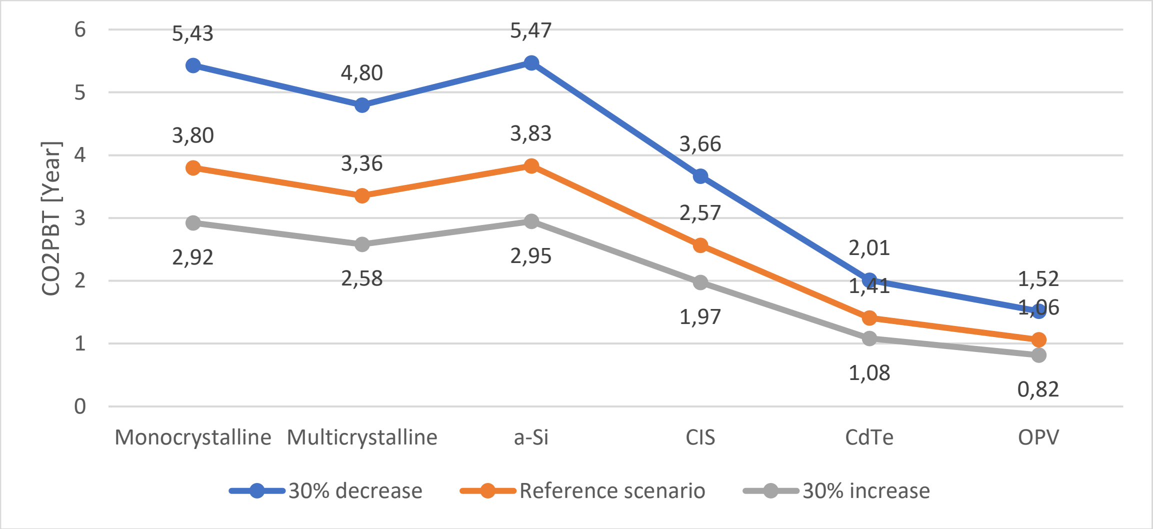

Figure 77: Sensitivity analysis of the CO_2PBT with respect to modules conversion efficiency (Own production).

Figure 77 demonstrates the significant impact of the modules conversion efficiency on the CO_2PBT. For all technologies, increasing the modules conversion efficiency by 30% with respect to the value in the reference scenario causes a reduction of the CO_2PBT by 23.08%. The mathematical explanation is given by the fact that the numerator of the CO_2PBT is represented by the $CO_{2\text{-eq}}$ emissions over the life cycle and it remains unchanged, while the denominator is the yearly $CO_{2\text{-eq}}$ emissions avoided and it grows by 30%. Consequently, the CO_2PBT is reduced by 23.08%. Conversely, a reduction of 30% of the modules conversion efficiency with respect to the value in the reference scenario brings to a 42.86% increase of the CO_2PBT across all technologies. This is explained by the fact that decreasing the modules conversion efficiency by 30% induces a reduction of the same percentage of the denominator of the CO_2PBT, so that the CO_2PBT grows by 42.86%.

5.4.3. Benefits from the end-of-life phase

In the current subsection it is performed an analysis considering the inclusion of benefits from the end-of-life phase. The results obtained are compared with the reference scenario, that does not consider the benefits from the end-of-life phase. Figure 78 provides the results for the first impact indicator, the cumulative energy demand.

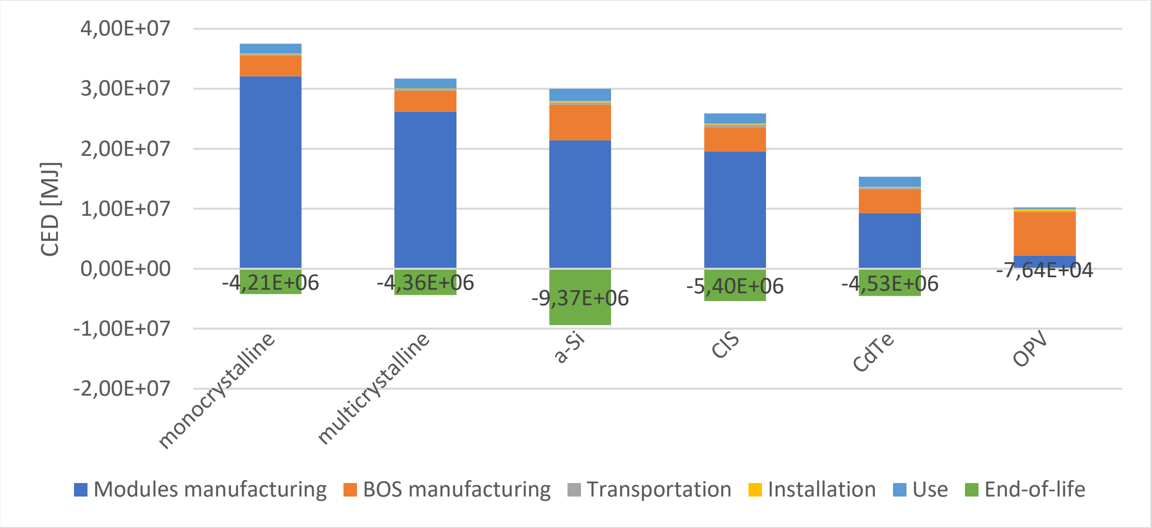

Figure 78: CED with inclusion of benefits from the end-of-life (Own production).

Figure 78 demonstrates that the absolute value of the impact in terms of cumulative energy demand of the end-of-life phase comprehensive of benefits varies widely across technologies. The impact ranges from -7.64*10^4 MJ for OPV technology to -9.37*10^6 MJ for a-Si technology. The wide variation of the impact across technologies is given by the different processes and related benefits considered. For example, the end-of-life phase of OPV technology is modeled with the factor of -7.85 MJ/m^2 for the impact in terms of cumulative energy demand of the recycling process and with the CED to transport components from the installation location to the processing facility. On the other hand, the end-of-life phase of a-Si technology is modeled considering the factor of -609.46 MJ/m^2 for the impact in terms of cumulative energy demand. Furthermore, it is observed in Figure 78 that the absolute values of the impact in terms of CED of the end-of-life phase inclusive of benefits are higher for second generation technologies than for first generation technologies. The difference is driven by the higher specific areas [m^2/kW] of second-generation technologies, so that the technology-specific values of the impact of the end-of-life phase inclusive of benefits [MJ/m^2] indicated in Table 9 are multiplied by a larger area. The impacts in terms of CED of the end-of-life phase are indicated as a negative number, since they can decrease the CED over the life cycle of the system. Accordingly, in Figure 79 the CED of the scenario considering the reduction of the CED due to benefits from the end-of-life is compared with the CED of the reference scenario without benefits. In addition, Figure 79 indicates the percentage reduction of the CED over the life cycle with respect to the reference scenario because of the inclusion of benefits from the end-of-life.

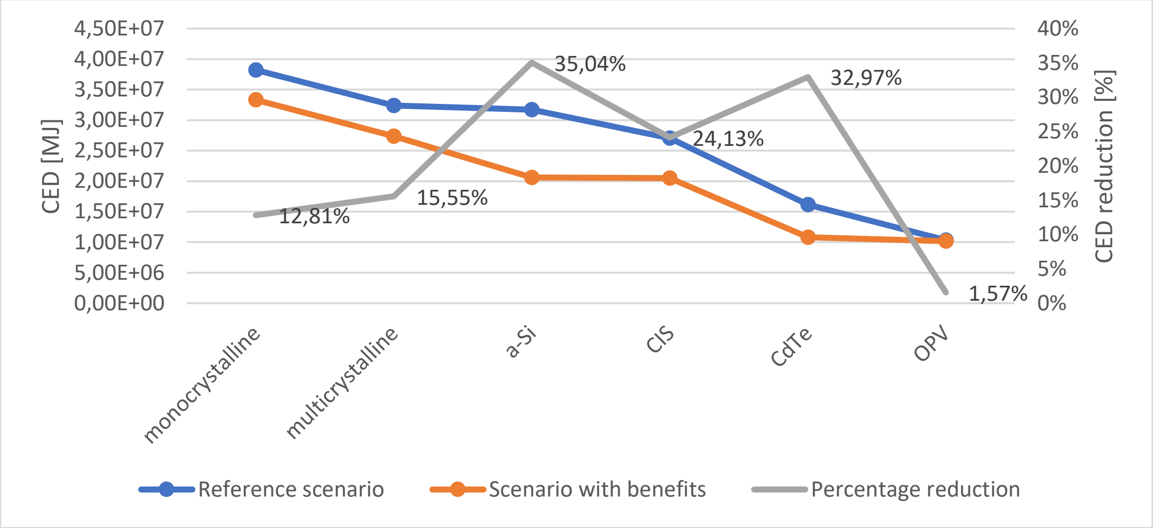

Figure 79: Comparison of the CED in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production).

Figure 79 demonstrates that the inclusion of benefits from the end-of-life can bring to a consistent variation of the cumulative energy demand with respect to the reference scenario. The percentage reduction of the CED with respect to the reference scenario ranges from 1.57% for OPV technology to 35.04% for a-Si technology. The wide variation of the percentage reduction across technologies is driven by the different processes and related benefits considered, as presented while analyzing Figure 78. In addition, it is noticed in Figure 79 that the percentage reduction of the CED is lower for first generation technologies with respect to second generation technologies. This is justified by the higher absolute values of the impact of the end-of-life phase inclusive of benefits for second generation technologies, as observed when analyzing Figure 78, as well as by the higher CED over the life cycle of first-generation technologies in the reference scenario. Finally, it is observed that in the scenario with benefits the ranking of technologies from the highest to the lowest CED remains unchanged with respect to the reference scenario and it is the following: monocrystalline, multicrystalline, a-Si, CIS, CdTe, OPV.

The results obtained are compared with the literature. For example, Held and Ilg (62) analyze the recycling process of a system based on CdTe technology and confirm that the benefits due to material recycling and energy recovery outweigh the impact of the end-of-life phase. Consequently, the scholars compute that the end-of-life phase brings to a reduction of the primary energy demand over the life cycle of the system of 12.5 MJ/m^2 (62).

Figure 80 provides the results for the second impact indicator, the global warming potential.

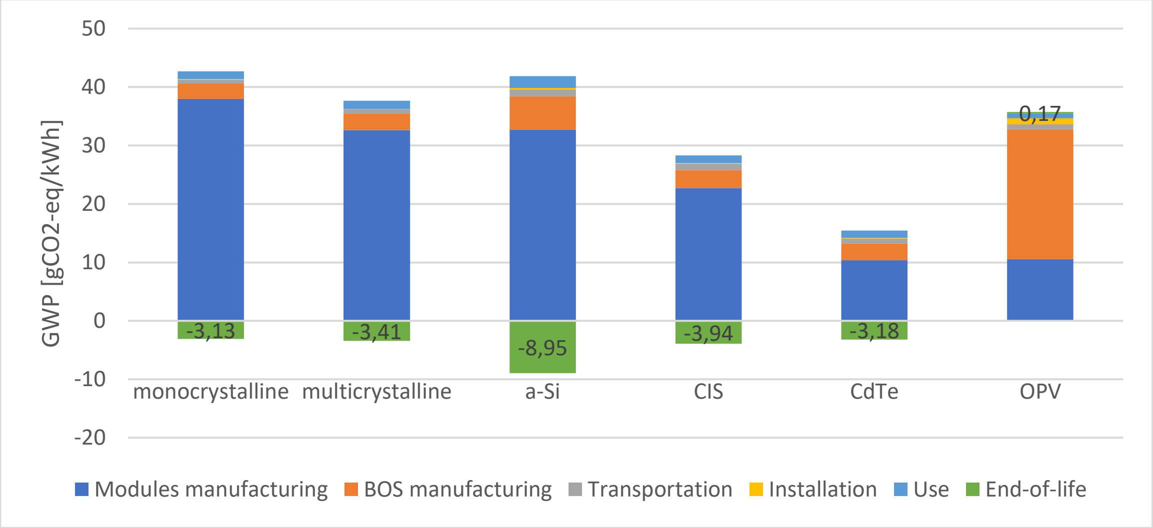

Figure 80: GWP with inclusion of benefits from the end-of-life (Own production).

Figure 80 demonstrates that the impact in terms of global warming potential of the end-of-life phase comprehensive of benefits varies widely across technologies. The GWP of the end-of-life phase ranges from +0.17 $gCO_{2\text{-eq}}$/kWh for OPV technology to -8.95 $gCO_{2\text{-eq}}$/kWh for a-Si technology. The wide variation of the impact across technologies is given by the different processes and related benefits considered. For example, the end-of-life phase of OPV technology is modeled including the impact of the recycling process in terms of $CO_{2\text{-eq}}$ emission, computed from the factor of -7.85 MJ/m^2 for the impact in terms of cumulative energy demand, the grid conversion efficiency from primary energy to electricity, and the grid carbon intensity, as well as the $CO_{2\text{-eq}}$ emissions released to transport components from the installation location to the processing facility. On the other hand, the end-of-life phase of a-Si technology is modeled considering the factor of -609.46 MJ/m^2 for the impact in terms of cumulative energy demand, the grid conversion efficiency from primary energy to electricity, and the grid carbon intensity. The GWP greater than zero for the end-of-life phase of OPV technology is due to the fact that the $CO_{2\text{-eq}}$ emissions released in the transportation of components from the installation location to the processing facility are greater in absolute value than the impact in terms of $CO_{2\text{-eq}}$ emissions of the recycling process inclusive of benefits. Furthermore, it is detected in Figure 80 that the absolute values of the impact in terms of GWP of the end-of-life phase are higher for a-Si and CIS technologies than for first generation technologies. The difference is driven by the higher specific areas [m^2/kW] of a-Si and CIS technologies compared to the first-generation ones, so that the technology-specific values of the impact of the end-of-life phase inclusive of benefits [MJ/m^2] indicated in Table 9 are multiplied by a larger area. The impact in terms of GWP of the end-of-life phase inclusive of benefits is indicated as a negative number for all technologies except OPV, since it can decrease the GWP over the life cycle of the system. Accordingly, in Figure 81 the GWP of the scenario considering the reduction of the GWP due to benefits from the end-of-life phase is compared with the GWP of the reference scenario without benefits. In addition, Figure 81 indicates the percentage reduction of the GWP with respect to the reference scenario because of the inclusion of benefits from the end-of-life phase.

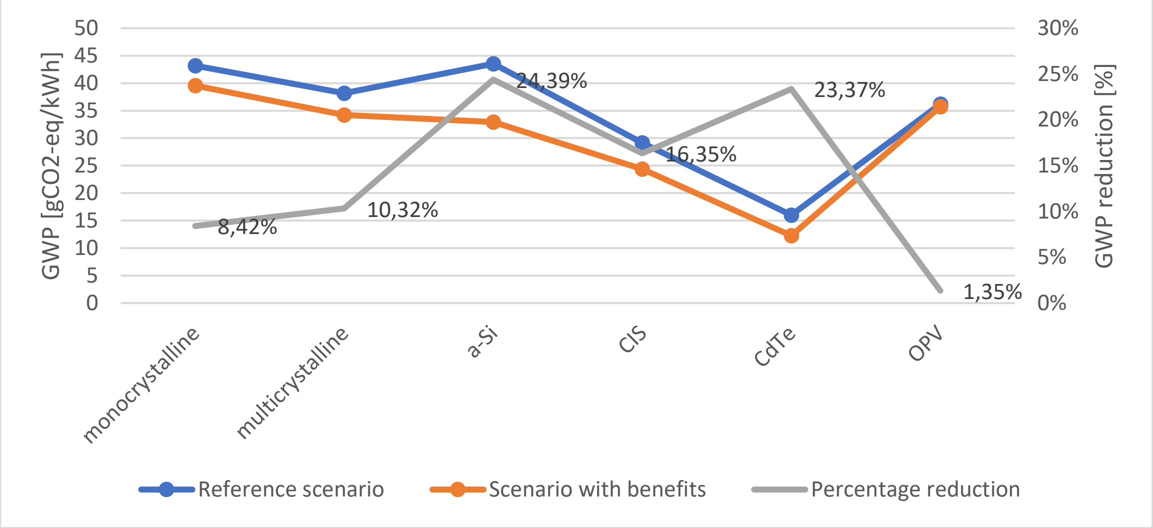

Figure 81: Comparison of the GWP in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production).

Figure 81 demonstrates that the inclusion of benefits from the end-of-life phase can bring to a consistent variation of the global warming potential with respect to the reference scenario. The reduction of the GWP with respect to the reference scenario ranges from 1.35% for OPV technology to 24.39% for a-Si technology. The large difference in the percentage reduction across the technologies is explained by the different processes and related benefits considered, as presented while analyzing Figure 80. In addition, it is observed that the percentage reduction of the GWP is lower for first generation technologies with respect to second generation technologies. This is justified by the higher absolute values of the impact in terms of GWP of the end-of-life phase inclusive of benefits in case of a-Si and CIS technologies with respect to first generation technologies, that was observed when analyzing Figure 80, as well as by the lower GWP over the life cycle in the reference scenario for CdTe technology with respect to the other first and second-generation technologies. Finally, it is detected that in the scenario with benefits the ranking of technologies from the highest to the lowest GWP is modified with respect to the reference scenario. In the scenario with the inclusion of benefits a-Si,

monocrystalline, and OPV technologies change their positions and the ranking of technologies from the highest to the lowest GWP becomes: monocrystalline, OPV, multicrystalline, a-Si, CIS, CdTe.
The results obtained are compared with the literature. For example, Held and Ilg (62) analyze the recycling process of a system based on CdTe technology and confirm that the benefits due to material recycling and energy recovery outweigh the impact of the end-of-life phase. Consequently, the scholars compute that the end-of-life phase brings to a reduction of the impact in terms of $CO_{2\text{-eq}}$ emissions over the life cycle of the system of 2.5 $kgCO_{2\text{-eq}}/m^2$ (62).

The results for the third impact indicator, the energy payback time, are provided in Figure 82, where the scenario considering the reduction of the EPBT due to benefits from the end-of-life phase is compared with the reference scenario. In addition, Figure 82 indicates the percentage reduction of the EPBT with respect to the reference scenario because of the inclusion of benefits from the end-of-life.

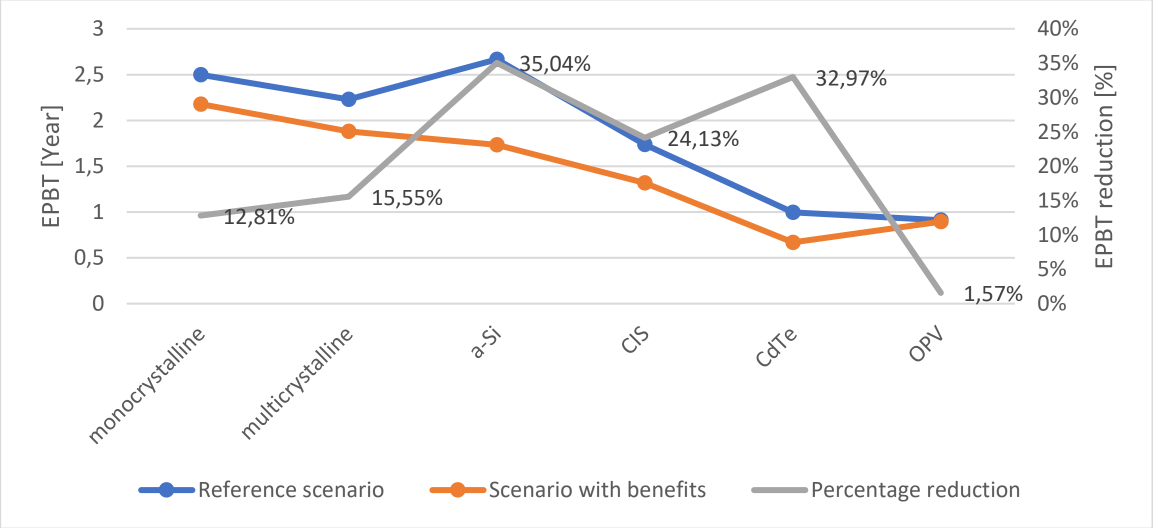

Figure 82: Comparison of the EPBT in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production).

Figure 82 demonstrates that the inclusion of benefits from the end-of-life can bring to a consistent variation of the energy payback time with respect to the reference scenario. The reduction of the EPBT with respect to the reference scenario ranges from 1.57% for OPV technology to 35.04% for a-Si technology. For all technologies, it is experienced the same percentage reduction observed for the cumulative energy demand and plotted in Figure 79. As a matter of fact, the numerator of the EPBT is the CED, while the denominator is the mean annual energy produced and it remains unchanged in the scenarios with and without benefits from the end-of-life. The large difference in the percentage reduction across technologies is explained by the different processes and related benefits considered. For example, the end-of-life phase of OPV technology is modeled with the factor of -7.85 MJ/m^2 for the impact in terms of cumulative energy demand of the recycling process and with the CED to transport components from the installation location to the processing facility. On the other hand, the end-of-life phase of a-Si technology is modeled considering the factor of -609.46 MJ/m^2 for the impact in terms of cumulative energy demand. Furthermore, it is observed that the percentage reduction of the EPBT is lower for first generation technologies with respect to second generation technologies. The difference is driven by the higher absolute values of the impact in terms of CED of the end-of-life phase inclusive of benefits for second generation technologies, that was observed while analyzing Figure 78. Finally, it is observed that in the scenario with benefits the ranking of technologies from the highest to the lowest EPBT is modified with respect to the reference scenario. In the scenario including the benefits, monocrystalline and multicrystalline become the technologies characterized by the highest EPBT, switching their positions in the ranking with a-Si technology, while CdTe becomes the technology with the lowest EPBT, switching its position with OPV technology.

The results obtained are compared with the literature. For example, Tsang et al. (170) analyze a system based on OPV technology and observes that the benefits due to energy recovery from the end-of-life phase decreases the EPBT with respect to the disposal to landfill.

The results for the fourth impact indicators, the CO_2 payback time, are provided in Figure 83, where the scenario considering the reduction of the CO_2PBT due to benefits from the end-of-life phase is compared with the reference scenario. In addition, Figure 83 indicates the percentage reduction of the CO_2PBT with respect to the reference scenario because of the inclusion of benefits from the end-of-life.

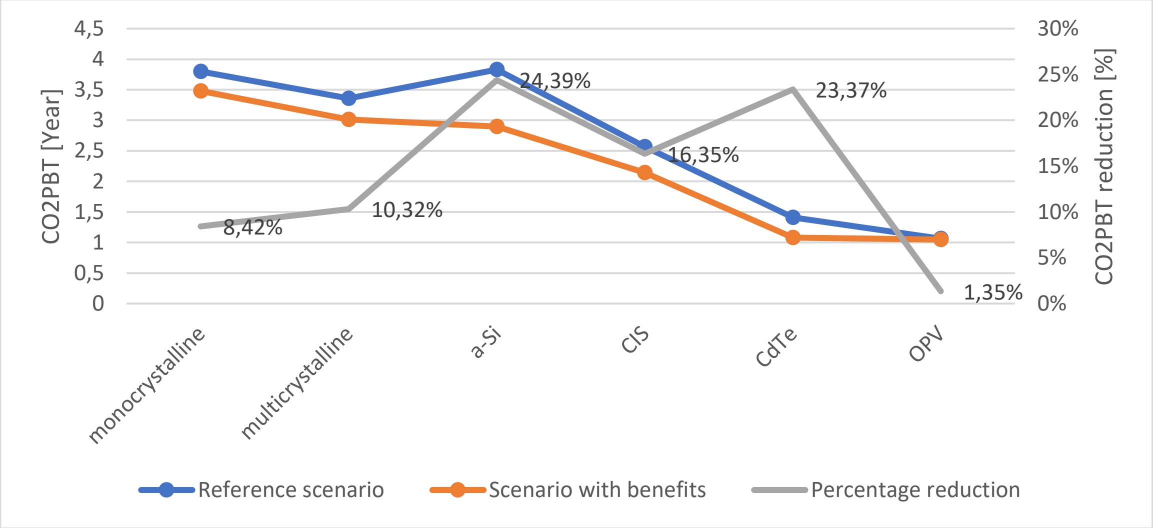

Figure 83: Comparison of the CO_2PBT in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production).

Figure 83 demonstrates that the inclusion of benefits from the end-of-life can bring to a consistent variation of the CO_2PBT with respect to the reference scenario. The reduction of the CO_2PBT with respect to the reference scenario ranges from 1.35% for OPV technology to 24.39% for a-Si technology. For all technologies, it is experienced the same percentage reduction observed for the global warming potential and plotted in Figure 81. As a matter of fact, the numerator of the CO_2PBT is represented by the $CO_{2\text{-eq}}$ emissions over the life cycle, and it is equal to the product of the GWP by the electricity produced over the lifetime, while the denominator is represented by the yearly $CO_{2\text{-eq}}$ emissions avoided and it remains unchanged in the scenarios with and without benefits from the end-of-life. The large difference in the percentage reduction across technologies is explained by the different processes and related benefits considered. For example, the end-of-life phase of OPV technology is modeled including the impact of the recycling process in terms of $CO_{2\text{-eq}}$ emission, computed from the factor of -7.85 MJ/m^2 for the impact in terms of cumulative energy demand, the grid conversion efficiency from primary energy to electricity, and the grid carbon intensity, as well as the $CO_{2\text{-eq}}$ emissions released to transport components from the installation location to the processing facility. On the other hand, the end-of-life phase of a-Si technology is modeled considering the factor of -609.46 MJ/m^2 for the impact in terms of cumulative energy demand, the grid conversion efficiency from primary energy to electricity, and the grid carbon intensity. Furthermore, it is observed that the percentage reduction of the CO_2PBT is lower for first generation technologies with respect to second generation technologies. The difference is explained by the higher absolute values of the impact in terms of GWP of the end-of-life phase inclusive of benefits for a-Si and CIS technologies with respect to first generation technologies, that was observed while analyzing Figure 80, as well as by the lower CO_2PBT in the reference scenario for CdTe technology with respect to other first and second-generation technologies. Finally, it is observed that in the scenario with benefits the ranking of technologies from the highest to the lowest CO_2PBT is modified with respect to the reference scenario. In the scenario including benefits, monocrystalline and multicrystalline become the technologies with the highest CO_2PBT, while a-Si technology changes its position in the ranking and becomes the technology with the third highest CO_2PBT.

6 Conclusions

6.1. Bottom line results

The current section provides a synthesis of the results obtained as well as the answer to the research questions identified.

The developed evaluation framework permitted to compare six different PV technologies with respect to four impact indicators, and was applied with reference to five different supply chain scenarios. Starting from the first impact indicator, the cumulative energy demand, it has been demonstrated that considering a fixed technology it varies in a limited manner across scenarios. For all technologies, the scenario with the highest CED is the Chinese supply. For all technologies except CIS, the scenario with the lowest CED is the Italian supply. On the other hand, while considering a fixed scenario the variation of the CED across technologies is considerable. For all scenarios, the ranking of technologies from the highest to the lowest CED is the following: monocrystalline, multicrystalline, a-Si, CIS, CdTe, OPV. Finally, it was observed that for first- and second-generation technologies modules manufacturing accounts for most of the CED over the life cycle, while for OPV technology BOS manufacturing is the most impactful phase.

Considering the second impact indicator, the global warming potential, it has been demonstrated that considering a fixed technology, the variation of the impact across scenarios is considerable. For all technologies except OPV, the ranking from the most to the least polluting scenario is the following: Chinese supply, Mixed supply, Out-of-Asia supply, German supply, Italian supply. The main driver of the variation of the GWP across scenarios is the grid carbon intensity of the country where modules are manufactured, for first- and second-generation technologies, and the grid carbon intensities of the countries where BOS components are manufactured, for OPV technology. Considering a fixed scenario, the variation of the GWP across technologies is considerable. In all scenarios except the Mixed supply and the Out-of-Asia supply, the ranking of technologies from the highest to the lowest GWP is the following: OPV, a-Si, monocrystalline, multicrystalline, CIS, CdTe. Furthermore, it was observed that CdTe is the technology with the lowest GWP across all scenarios. Finally, it was demonstrated that for first- and second-generation technologies, modules manufacturing phase accounts for most of the GWP over the life cycle, while for OPV technology BOS manufacturing is the

phase accounting for most of the impact in terms of GWP.
The third impact indicator, the energy payback time, shows a limited variation across scenarios while considering a fixed technology. For all technologies, the scenario with the highest EPBT is the Chinese supply. For all technologies except CIS, the scenario with the lowest EPBT is the Italian supply. Considering a fixed scenario, the variation of the EPBT across technologies is considerable and it was observed in all scenarios the same ranking of technologies from the highest to the lowest EPBT: a-Si, monocrystalline, multicrystalline, CIS, CdTe, OPV.
Considering the fourth impact indicator, the CO_2 payback time, it has been demonstrated that for a fixed technology, the variation of the indicator across scenarios is considerable. For all technologies except OPV, the ranking of scenarios from the highest to the lowest CO_2PBT is the following: Chinese supply, Mixed supply, Out-of-Asia supply, German supply, Italian supply. The main driver of the variation of the CO_2PBT across scenarios is the grid carbon intensity of the country where modules are manufactured for first- and second-generation technologies and the grid carbon intensities of the countries where BOS components are manufactured for OPV technology. Considering a fixed scenario, the variation of the CO_2PBT across technologies is considerable. For all scenarios, the ranking of technologies from the highest to the lowest CO_2PBT is the following: a-Si, monocrystalline, multicrystalline, CIS, CdTe, OPV.

In Chapter 3, it has been indicated that the objective of the current thesis consists in answering in the most exhaustive manner possible the research questions identified. Accordingly, the answers to the research questions identified will now be provided.
The first research question has been indicated as follows:

> RQ1: What are the trade-offs arising when multiple metrics evaluating more than one environmental problem are considered and how the usage of multiple metrics can help in taking decisions?

The results obtained represent an example of the trade-offs arising when comparing technologies over multiple indicators. For example, it was observed that the best performing technology in terms of EPBT and CO_2PBT is the OPV. On the other hand, OPV is the most polluting technology in terms of GWP in three out of five scenarios. This example demonstrates the inexistence of a single technology outperforming all the others across all the indicators considered. Consequently, trade-offs arise and the usage of multiple indicators is considered helpful in taking decisions.
Considering the RQ1 and the related gap indicated in Section 2.3, the current thesis contribute to the existing literature by performing an assessment over the four most

common metrics in LCA studies of PV technologies. It has been presented in the literature review the limited number of studies including results for the four most common indicators (CED, GWP, EPBT, CO_2PBT) and the importance of covering multiple impact indicators.

The second research question has been indicated as follows:

> RQ2: What is the influence of the different phases composing the life cycle on the environmental impact of PV technologies?

From the results obtained it emerges that some phases contribute the most to the environmental impact. Starting from the cumulative energy demand and considering first and second-generation technologies, some patterns are identified. First, modules manufacturing is the most impactful phase. Modules manufacturing is responsible for a share of the CED over the life cycle ranging from a minimum of 56.74%, observed for CdTe technology, to a maximum of 84.03%, observed for monocrystalline technology. Second, BOS manufacturing is the second most impactful phase. BOS manufacturing is responsible for a share of the CED ranging from a minimum of 9.01%, observed for monocrystalline technology, to a maximum of 24.17%, observed for CdTe technology. Third, use phase is the third most impactful phase. The impact of the use phase with respect to the total CED ranges from a minimum of 4.31%, observed for monocrystalline technology, to a maximum of 10.67%, observed for CdTe technology. Fourth, the thesis demonstrated that the impact of the end-of-life phase in terms of CED is limited: it is never higher than 4.93% of the CED. Furthermore, the transportation phase is responsible for a limited impact, accounting for a share of the CED ranging from a minimum of 0.48%, observed for monocrystalline technology, to a maximum of 3.21%, observed for CdTe technology. Lastly, installation is the phase accounting for the lowest impact: it is responsible for less than 0.92% of the CED across all technologies and scenarios considered. Considering OPV technology, some differences are observed with respect to first- and second-generation technologies. First, the most impactful phase is the BOS manufacturing, responsible for over 68.06% of the CED. Second, modules manufacturing is the second most impactful phase, being responsible for an impact ranging from 20.51% to 21.32% of the CED depending on the scenario considered. Third, transportation or installation phase is the third most impactful phase, depending on the scenario considered. For example, the transportation phase is responsible from 0.84% to 4.62% of the CED, while the impact of the installation phase is never higher than 3.35% of the CED. As with first- and second-generation technologies, it is confirmed for OPV technology that the impact in terms of CED of the end-of-life phase is limited, being responsible for a share of the total impact lower than 0.83% across all scenarios. Lastly, the impact of the use phase is limited and ranges from a minimum of 2.80% to a maximum of 2.91% of the CED.

Considering the global warming potential, some patterns are observed for first and second-generation technologies. First, modules manufacturing is the most impactful phase. Modules manufacturing is responsible for a share of the GWP ranging from a minimum of 55.94%, observed for CdTe technology, to a maximum of 87.96%, observed for monocrystalline technology. Second, BOS manufacturing is the second most impactful phase. It is responsible for a share of the GWP ranging from a minimum of 6.11%, observed for monocrystalline technology, to a maximum of 23.73%, observed for CdTe technology. Third, use phase is the third most impactful phase. It is responsible for a share of the GWP ranging from a minimum of 3.02%, observed for monocrystalline technology, to a maximum of 10.37%, observed for CdTe technology. Fourth, the thesis demonstrated that the impact of the end-of-life phase in terms of GWP is limited for all technologies. The share of the GWP due to the end-of-life phase is never higher than 4.80%. Furthermore, the transportation phase is responsible for a share of the GWP ranging from a minimum of 1.24%, observed for monocrystalline technology, to a maximum of 7.46%, observed for CdTe technology. Finally, the installation is the least impactful phase. The share of the GWP due to the installation phase is never higher than 0.90%.

Considering OPV technology, some differences are observed with respect to the patterns presented for first- and second-generation technologies. First, BOS manufacturing is the most impactful phase in terms of GWP. It is responsible for over 61.44% of the GWP across all scenarios. Second, modules manufacturing is the second most impactful phase, being responsible from 19.62% to 29.15% of the GWP. Third, transportation or installation phase is the third most impactful phase, depending on the scenario considered. For example, the transportation phase is responsible from 2.16% to 10.42% of the GWP, while the impact of the installation phase is never higher than 3.26% of the GWP. As with first- and second-generation technologies, the thesis demonstrated that the impact of the end-of-life phase in terms of GWP is limited, being responsible for a share of the GWP never higher than 2.07%. Finally, the use phase accounts for a limited share of the impact, being responsible from 1.68% to 2.83% of the GWP.

In addition, the sensitivity analysis demonstrated that the benefits from the end-of-life phase can significantly reduce the impact of PV technologies. Depending on the technology considered, the inclusion of benefits from the end-of-life brings to a reduction of the CED ranging from 1.57% to 35.04% with respect to the reference scenario, while the reduction of the GWP ranges from 1.35% to 24.39%.

Considering the RQ2 and the related gap, the current thesis contributes to the existing literature by proposing a cradle-to-grave assessment of PV technologies, as well as by including the evaluation of benefits from the end-of-life. As a matter of fact, it has been mentioned in the literature review the scarcity of studies covering the full life cycle and the importance of assessing the impact of end-of-life phase.

The third research question is the following:

> RQ3: How does the environmental impact of PV technologies change depending on the manufacturing locations of the different components of the system?

The results obtained demonstrate that the impact of PV technologies over the indicators considered varies depending on the supply chain scenario examined. Starting from the cumulative energy demand and the energy payback time, it has been demonstrated that for all technologies the maximum values of the impact indicators correspond to the Chinese supply scenario, while the minimum values correspond to the Italian supply scenario for all technologies except CIS. The variation from the minimum to the maximum value of the indicators ranges from 0.59% for monocrystalline technology to 3.96% for OPV technology. Consequently, it is concluded that the location of manufacturing of the components of the PV system has a limited impact on the energy related indicators. Considering the global warming potential and the CO_2 payback time, it has been demonstrated that for all technologies the maximum and the minimum values of the impact indicators correspond to the Chinese supply scenario and the Italian supply scenario, respectively. In addition, for all technologies the indicators grow more than 58.85% from the minimum to the maximum value. It is concluded that the location of manufacturing of the components of the PV system has a significant impact on the $CO_{2\text{-eq}}$ emissions related indicators.

Considering the RQ3 and the related gap, the current thesis represents a valuable contribution to the existing literature, since it includes scenarios considering different locations for the manufacturing of the various components of the PV system. As a matter of fact, as mentioned in the literature review, in most cases modules and BOS components are not imported from the same country. The current study is considered a relevant contribution to the literature since it has been demonstrated in Paragraph 2.2.3.2 the limited number of papers considering different geographies for the manufacturing of the various components of the PV system.

The fourth research question is the following:

> RQ4: How does the environmental impact change depending on the PV technology considered?

The results obtained demonstrate that the environmental impact changes widely depending on the PV technology considered. Starting from the cumulative energy demand, it has been observed for all scenarios the same ranking of technologies from the highest to the lowest CED: monocrystalline, multicrystalline, a-Si, CIS, CdTe, OPV. The variation of the CED across technologies is considerable: in all scenarios, it was observed that the CED grows more than 3.5 times from the least impactful to the most impactful technology. Considering the global warming potential, in all scenarios except the Mixed supply and the Out-of-Asia supply, the ranking of technologies from the highest to the lowest GWP is: OPV, a-Si, monocrystalline, multicrystalline, CIS, CdTe. Furthermore, CdTe is the technology with the lowest GWP in all scenarios. The variation of the GWP across technologies is considerable: it was observed for all scenarios that the GWP grows more than 2.6 times from the least impactful to the most impactful technology. Regarding the energy payback time, it was observed for all scenarios the same ranking of technologies from the highest to the lowest EPBT: a-Si, monocrystalline, multicrystalline, CIS, CdTe, OPV. The variation of the EPBT across technologies is significant: it was observed for all scenarios that the EPBT grows more than 2.8 times from the lowest value, corresponding to OPV technology, to the highest value, corresponding to a-Si technology. Considering the CO_2 payback time, it was observed that for all scenarios the ranking of technologies from the highest to the lowest CO_2PBT is the following: a-Si, monocrystalline, multicrystalline, CIS, CdTe, OPV. The variation of the CO_2PBT across technologies is considerable: it was observed for all scenarios that the CO_2PBT grows more than 2.7 times from the lowest value, corresponding to OPV technology, to the highest value, corresponding to a-Si technology.

Considering the RQ4 and the related gap, the current thesis contributes to the existing literature by performing an assessment of six PV technologies, including the most diffused options as well as OPV technology. As mentioned in the literature review, a limited number of studies include a comparison of multiple technologies, that is considered relevant since it can provide useful industrial and policy implications.

Now that the answers to the research questions have been provided, it is mentioned a further contribution of the thesis. It is considered that the developed evaluation framework represents a valuable contribution to the literature. First, it allows to assess the environmental impact of a wide array of PV technologies. In the literature review, it has been mentioned the limited number of tailored models including multiple PV technologies within the analysis, as well as the importance of comparing multiple PV technologies. Second, the evaluation framework covers the full life cycle and includes the possibility to assess the benefits from the end-of-life phase. It has been observed in the literature review the shortage of tailored models covering the full life cycle, as well as the importance of the end-of-life phase for the future sustainability of PV technologies.

Finally, it is noticed that the highest global warming potential computed across the scenarios and the technologies analyzed is equal to 53.79 gCO_{2-eq}/kWh and corresponds to OPV technology in the Chinese supply scenario. Also, the sensitivity analyses assessed scenarios with a reduction in irradiation or in modules conversion efficiency with respect to the reference scenario, and the corresponding GWP computed is at maximum equal to 62.19 gCO_{2-eq}/kWh, and corresponds to a-Si technology. It is observed that the life cycle emissions of conventional electricity generation technologies are at least one order of magnitude greater than the results mentioned. For example, the review published by the NREL indicates a median value of the GWP over the life cycle of 486 gCO_{2-eq}/kWh for the electricity produced from gas, 840 gCO_{2-eq}/kWh for the electricity produced from oil, and 1001 gCO_{2-eq}/kWh for the electricity produced from coal (39). The conclusion is that regardless of the PV technology considered and the scenario modeled in the current thesis, PV represents a valuable technology to decarbonize the energy sector.

6.2. Industrial and policymaking implications

The present thesis has implications for players in the solar photovoltaic industry. Starting from modules and components manufacturers, the current study provides suggestions on the parameters having the highest influence on impact indicators, thus fostering the adoption of environmentally friendlier alternatives. For example, given the relevant impact on the global warming potential of the carbon intensity of the electricity consumed in the modules manufacturing process, a modules manufacturer may choose to purchase green electricity or to install in-situ renewable power plants, to make the electricity mix used greener. Furthermore, the present thesis provides suggestions for decision makers in modules and BOS components procurement to support choices aimed at reducing the environmental impact depending on the location of manufacturing of the components purchased.
Moving to another actor in the photovoltaic landscape, the current thesis provides useful suggestions for policymakers. First, by demonstrating the lower global warming potential of PV technologies with respect to conventional generation technologies, it confirms that photovoltaic represents an important technology in the decarbonization of the energy sector. Consequently, the current study provides a scientific basis for the support to photovoltaic technologies. Second, by proposing a comparison of a wide array of PV technologies, the present thesis provides suggestions for policymakers on the specific incentives to be defined for the different PV technologies, depending on their environmental impact. Third, the current study demonstrates the limited environmental impact of the end-of-life phase with respect to the full life cycle as well as the relevant benefits arising from material recycling. Given the findings of the thesis and the fundamental role played

by the end-of-life phase in the long-term sustainability of photovoltaic technologies, policymakers are called to action to foster the recycling of PV modules and BOS components. Fourth, by demonstrating the relevant impact on greenhouse gas related indicators of the grid carbon intensity of the country where modules and BOS components are manufactured, the current thesis highlights the importance of consistent policies to promote the decarbonization of the electricity sector. Lastly, by demonstrating the lower environmental impact associated with scenarios involving the manufacturing of components in Italy or in Germany with respect to the manufacturing in China, the current study suggests to policymakers the benefits arising due to the creation and growth of a PV supply chain in countries characterized by a greener electricity mix with respect to China.

6.3. Limitations and avenues for future research

It is important to highlight the limitations of the current study.

First, the developed evaluation framework only includes energy and greenhouse gas emissions related indicators. As presented in Section 1.3, energy consumption and greenhouse gas emissions are not the only impact categories associated with PV technologies. For example, other impact categories are represented by the water consumption or the land footprint. Second, in the developed evaluation framework it is assumed that all steps of the modules manufacturing process happen in the same country. As mentioned in Section 4.3, the adopted assumption does not fully reflect the complexity of PV supply chain. Similarly, it is assumed that the end-of-life phase takes place in the same country as the installation. As reported in Section 4.8, it is expected that trade of PV waste between countries will arise in the future, adding complexity to the analysis. Third, it is acknowledged the limited quality of the data applied to model the end-of-life phase of first- and second-generation technologies. As indicated in Section 4.8, data to model the end-of-life phase of first- and second-generation technologies are gathered from a source that models the end-of-life phase of CdTe technology using data from First Solar's recycling procedure, and apply corrective factors to model the end-of-life of other PV technologies starting from data for CdTe technology. As a matter of fact, it was observed in Paragraph 2.2.5.7 that end-of-life practices are still under development and a lack of data is observed in the domain. Lastly, in the current study it is not considered the evolution of the grid carbon intensity over the lifetime of the PV system. It is observed that most of the impact of PV technologies in terms of energy and $CO_{2\text{-eq}}$ emissions related indicators is due to the modules manufacturing and BOS manufacturing phases, so that the variation of the grid carbon intensity over the lifetime of the PV system will likely have a limited impact on results. Nevertheless, considering the evolution of the grid carbon intensity over time would permit to create scenarios closer to reality.

After the presentation of the limitations of the current study, the avenues for future research are suggested. They are divided in the two following categories: limitation related, and non-limitation related.
The limitation related avenues for future research are defined as arising from the limitations highlighted at the beginning of the current section. Consequently, the first suggestion for future research consists in extending the developed evaluation framework to more impact categories, such as the land footprint or the water consumption. A second avenue for future research consists in a finer modeling of the modules manufacturing process, permitting to consider different countries for the various manufacturing steps, as well as the inclusion of scenarios taking into consideration the trade of PV waste between countries. Third, an improvement of the current study consists in a further investigation of the end-of-life stage with the availability of more and higher quality data in the future. Lastly, future studies could include a time related perspective by taking into account the evolution of the grid carbon intensity, to evaluate its effect on the environmental impact indicators.
The second category of avenues for future research is defined as not directly related to the limitations indicated at the beginning of the current section. The first avenue for future research is represented by the inclusion of more technological options within the analysis. The inclusion of more technological options breaks down into three alternatives. The first alternative consists in the expansion to other PV configurations, such as BIPV, agrivoltaic, and floating PV. The second alternative is related to the inclusion of more modules technologies in the study, such as the perovskite one. The third alternative consists in the inclusion of additional components, such as storage systems or tracking systems, within the boundaries of the analysis. A second avenue for future research, as mentioned in Section 2.4, consists in completing LCA studies by using primary and updated data, to shed light on their influence on impact indicators. A third avenue for future research consists in expanding the current study to more geographies. The present thesis focused on a PV system installed in Italy and considered five different supply chain scenarios. Nevertheless, the study can be expanded to more geographies, both in terms of installation locations and supply chain scenarios. Finally, it is mentioned as an interesting avenue for future research the evaluation of the social and economic impact of photovoltaic technologies, to have a comprehensive evaluation of their sustainability.

Bibliography

1. International Energy Agency. *World Energy Outlook 2022.* 2022.

2. IPCC. *Sixth Assessment Report.* 2021.

3. European Commission. Accordo di Parigi. *Commissione Europea.* [Online] https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_it.

4. —. Cause dei cambiamenti climatici. *Commissione Europea.* [Online] https://ec.europa.eu/clima/climate-change/causes-climate-change_it.

5. World Resource Institute. 4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors. [Online] https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors.

6. IRENA. Solar energy. [Online] https://www.irena.org/solar.

7. Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti. *Piano nazionale integrato per l'energia e il clima.* 2019.

8. Italy plans 50 GW PV, 18.4 GW wind to meet 2030 target. *Renewables Now.* [Online] https://renewablesnow.com/news/italy-plans-50-gw-pv-184-gw-wind-to-meet-2030-target-639356/#:~:text=Italy%20will%20aim%20to%20reach%2050%20GW%20of,plan%2C%20the%20target%20for%20wind%20is%2018.4%20GW..

9. Letcher, T., Fthenakis, V. *A comprehensive guide to solar energy systems.* 2018.

10. IRENA. *Renewable energy statistics 2022.* 2022.

11. Sundaram et al. *Solar Photovoltaic Technology Production: potential environmental impacts and implication for governance.* 2016.

12. *Review on Life Cycle Assessment of Solar Photovoltaic Panels.* Muteri et al. s.l. : Energies, 2019.

13. *Environmental and damage assessment of transparent solar cells compared with first and second generations using the LCA approach.* Zahedi et al. 2022.

14. International Energy Agency. *Trends in photovoltaic applications 2022.* 2022.

15. —. *Trends in Photovoltaic Applications 2021.* 2021.

16. Urbina, A. *Sustainable solar electricity.* s.l. : Springer, 2022.

17. Fraunhofer Institute for Solar Energy Systems, ISE. *PHOTOVOLTAICS REPORT.* 2022.

18. *Environmental impacts of solar energy systems: A review.* Rabaia et al. s.l. : Science of the Total Environment, 2021, Vol. 754.

19. International Energy Agency. Renewables 2021 Data Explorer. *IEA.* [Online] https://www.iea.org/articles/renewables-2021-data-explorer?mode=market&region=World&publication=2021&product=PV+commercial+systems%2CPV+residential+systems%2CPV+utility-scale+systems%2CPV+off-grid.

20. —. *Renewables 2019.* 2019.

21. Agrivoltaics. *Fraunhofer ISE.* [Online] https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/agrivoltaics.html.

22. *Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation.* Kim et al. 2012.

23. *Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends.* Fthenakis, V., Leccisi, E. s.l. : Progress in Photovoltaics, 2021.

24. European Commission. *Preparatory study for solar photovoltaic modules, inverters and systems.* 2020.

25. *Life cycle assessment of grid-connected power generation from metallurgical route multi-crystalline silicon photovoltaic system in China.* Yu et al. s.l. : Applied Energy, 2017, Vol. 185.

26. *Life Cycle Assessment for Balance-of-System of Photovoltaic Energy Systems* . Wang et al. 2022.

27. International Energy Agency. *Methodology Guidelines on Life Cycle Assessment of Photovoltaic.* 2020.

28. Department of Energy. Solar Photovoltaic Manufacturing Basics. *energy.gov.* [Online] https://www.energy.gov/eere/solar/solar-photovoltaic-manufacturing-basics.

29. Eurostat. Glossary:Carbon dioxide equivalent. [Online] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent.

30. —. Glossary:Greenhouse gas (GHG). [Online] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Greenhouse_gas_(GHG).

31. International Energy Agency. CO2 emissions. [Online] https://www.iea.org/reports/global-energy-review-2021/co2-emissions.

32. International Enrgy Agency. *Special Report on Solar PV Global Supply Chains* . 2022.

33. *Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook.* Tawalbeh et al. s.l. : Science of the Total Environment, 2020, Vol. 759.

34. *Environmental impacts from the installation and operation of large-scale solar power plants.* Turney, D., Fthenakis, V. s.l. : Renewable and Sustainable Energy Reviews, 2011, Vol. 15.

35. *A True Hybrid Solar Wind Turbine Electric Generator System for Smaller Hybrid Renewable Energy Power Plants* . Al-Ajmi et al. 2018.

36. *A Life Cycle Assessment Model for Quantification of Environmental Footprints of a 3.6 kWp Photovoltaic System in Bangladesh.* Rahman et al. s.l. : Int. Journal of Renewable Energy Development, 2019, Vol. 8.

37. *An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand.* Eskew et al. s.l. : Renewable Energy, 2018, Vol. 123.

38. *Environmental Impact and Levelised Cost of Energy Analysis of Solar Photovoltaic Systems in Selected Asia Pacific Region: A Cradle-to-Grave Approach.* Ludin et al. . 2020.

39. NREL. *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update.* 2021.

40. Morais et al. Heavy Metals and Human Health. 2012.

41. *An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use.* Sengul, H., Theis, T. s.l. : Journal of Cleaner Production, 2011, Vol. 19.

42. *A review of Safety, Health and Environmental (SHE) issues of solar energy system.* Aman et al. s.l. : Renewable and Sustainable Energy Reviews, 2015, Vol. 41.

43. *Environmental impacts from the solar energy technologies.* Tsoutsos et al. s.l. : Energy Policy, 2005, Vol. 33.

44. *Water use of electricity technologies: A global meta-analysis.* Jin et al. . s.l. : Renewable and Sustainable Energy Reviews, 2019, Vol. 115.

45. *Life-cycle uses of water in U.S. electricity generation.* Fthenakis, V., Kim, H. s.l. : Renewable and Sustainable Energy Reviews, 2010, Vol. 14.

46. European Commission. *Life cycle assessment for the impact assessment of policies.* 2016.

47. *Life Cycle Analysis (LCA) of photovoltaic panels: A review.* Gerbinet et al. s.l. : Renewable and Sustainable Energy Reviews, 2014, Vol. 38.

48. NREL. Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics. [Online] https://www.nrel.gov/docs/fy13osti/56487.pdf.

49. Commission, European. European Platform on Life Cycle Assessment (LCA). [Online] https://ec.europa.eu/environment/ipp/lca.htm.

50. European Commission. *General guide for Life Cycle Assessment - Detailed guidance.* 2010.

51. Città Metropolitana di Milano. Valutazione del ciclo di vita: principi e quadro di riferimento. [Online] https://www.cittametropolitana.mi.it/export/sites/default/Responsabilita_sociale_impresa/Documenti/14040_2006.pdf.

52. Life Cycle Assessment (LCA). *European Commission.* [Online] https://eplca.jrc.ec.europa.eu/lifecycleassessment.html.

53. ISO 14044: Environmental Management - Life cycle assessment - requirements and guidelines. [Online] https://wapsustainability.com/wp-content/uploads/2020/11/ISO-14044.pdf.

54. Nakamura, S., Nansai, K. Input–Output and Hybrid LCA. *Special Types of Life Cycle Assessment.* 2016.

55. *Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA.* Yang et al. s.l. : Journal of Cleaner Production, 2017, Vol. 150.

56. *A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels .* Ansanelli et al. . s.l. : Applied Energy , 2021, Vol. 290.

57. *Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels.* Latunussa et al. s.l. : Solar Energy Materials & Solar Cells, 2016, Vol. 156.

58. *High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment* . Dias et al. s.l. : Renewable and Sustainable Energy Reviews , 2022, Vol. 169.

59. Ecoinvent . ecoinvent Database. [Online] https://ecoinvent.org/the-ecoinvent-database/.

60. *Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation.* Laleman et al. s.l. : Renewable and Sustainable Energy Reviews, 2011, Vol. 15.

61. *The Role of National Energy Policies and Life Cycle Emissions of PV Systems in Reducing Global Net Emissions of Greenhouse Gases.* Lima et al. s.l. : Energies, 2021.

62. *Update of environmental indicators and energy payback time of CdTe PV systems in Europe.* Held, M., Ilg, R. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2011, Vol. 19.

63. *Life cycle assessment of electricity generated by photovoltaic systems manufactured in Europe and installed in buildings in the city of Rome* . Santoli et al. 2010.

64. GaBi LCA Databases. *Sphera.* [Online] https://gabi.sphera.com/international/databases/gabi-databases/.

65. *Environmental performance of dye-sensitized solar cells based on natural dyes* . Błaszczyk et al. s.l. : Solar Energy , 2021, Vol. 215.

66. *Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries.* Üçtuğ, F., Azapagic, A. s.l. : Science of the Total Environment, 2018, Vol. 643.

67. Primary vs. secondary data – What's the best in LCA? *ecochain.* [Online] https://ecochain.com/knowledge/primary-vs-secondary-data-in-lca/.

68. *Life cycle assessment of different chalcogenide thin-film solar cells* . Resalati et al. s.l. : Applied Energy , 2022, Vol. 313.

69. *Advanced materials for emerging photovoltaic systems – Environmental hotspots in the production and end-of-life phase of organic, dye-sensitized, perovskite, and quantum dots solar cells* . Gressler et al. s.l. : Sustainable Materials and Technologies , 2022, Vol. 34.

70. *Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process.* Huang et al. . s.l. : Solar Energy, 2017, Vol. 143.

71. Data Releases. *ecoinvent .* [Online] https://ecoinvent.org/the-ecoinvent-database/data-releases/#1598281291261-311ce343-ec92.

72. *Energy balance and carbon footprint of very large-scale photovoltaic power plant.* Pamponet et al. . 2021.

73. *Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method.* Rashedi, A., Khanam, T. 2020.

74. *A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory.* Muller et al. s.l. : Solar Energy Materials ans Solar Cells, 2021, Vol. 230.

75. *Comparative life cycle assessment of fixed and single axis tracking systems for photovoltaics.* Antonanzas et al. s.l. : Journal of Cleaner Production, 2019, Vol. 240.

76. *Lifecycle climate impacts and economic performance of commercial-scale solar PV systems: A study of PV systems at Nevada's Desert Research Institute (DRI).* Liu et al. s.l. : Solar Energy, 2015, Vol. 119.

77. *Life Cycle Assessment of Disposed and Recycled End-of-Life Photovoltaic Panels in Australia.* Singh et al. 2021.

78. *Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review.* Ludin et al. s.l. : Renewable and Sustainable Energy Reviews, 2018, Vol. 96.

79. *Life cycle assessment of semi-transparent photovoltaic window applied on building.* Li et al. . s.l. : Journal of Cleaner Production, 2021, Vol. 295.

80. *Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea.* Kim et al. s.l. : Solar energy, 2014, Vol. 99.

81. *Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems.* Kim et al. s.l. : Solar energy, 2014, Vol. 103.

82. *What Are the Energy and Environmental Impacts of Adding Battery Storage to Photovoltaics? A Generalized Life Cycle Assessment.* Raugei et al. . s.l. : Energy technology, 2020.

83. *Energy and environmental impacts of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: A life-cycle approach .* Nordin et al. s.l. : Journal of Cleaner Production, 2022, Vol. 335.

84. *Environmental performance evaluation of a grid-independent solar photovoltaic power generation (SPPG) plant.* Akinyele. s.l. : Energy, 2017, Vol. 130.

85. *Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems.* Peng et al. s.l. : Renewable and Sustainable Energy Reviews, 2013, Vol. 19.

86. *Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study .* Wu et al. . s.l. : Energy Procedia, 2017, Vol. 105.

87. *Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems.* Bayod-Rujula et al. . s.l. : Energy, 2011, Vol. 36.

88. *Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies.* Chatzisideris et al. s.l. : Solar Energy Materials & Solar Cells, 2016, Vol. 156.

89. LCIA: the ReCiPe model. *National institute for public health and environment.* [Online] https://www.rivm.nl/en/life-cycle-assessment-lca/recipe.

90. *Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: A case study for Mexico .* Santoyo-Castelazo et al. s.l. : Journal of Cleaner Production , 2021, Vol. 316.

91. *Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade.* Yang et al. . s.l. : Journal of Cleaner Production, 2015, Vol. 94.

92. ReCiPe. *Pré sustainability.* [Online] https://pre-sustainability.com/articles/recipe/.

93. *Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong.* Dong., Y., NG, S. s.l. : Int J Life Cycle Assess, 2014.

94. *Techno-economic and environmental sustainability of industrial-scale productions of perovskite solar cells .* Zhang et al. . s.l. : Renewable and Sustainable Energy Reviews , 2022, Vol. 158.

95. *Net energy and cost benefit of transparent organic solar cells in building-integrated applications.* Anctil et al. s.l. : Applied Energy, 2020, Vol. 261.

96. *A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells.* Tsang et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2015, Vol. 24.

97. *Life Cycle Assessment of Two Experimental Recycling Processes for c-Si Solar Modules.* Monteiro Lunardi et al. 2019.

98. *Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels.* Maani et al. s.l. : Science of the Total Environment, 2020, Vol. 735.

99. *Influence of Waste Management on the Environmental Footprint of Electricity Produced by Photovoltaic Systems.* Herceg et al. 2020.

100. Life Cycle Assessment Software Tools – Overview. *Ecochain.* [Online] https://ecochain.com/knowledge/life-cycle-assessment-software-overview-comparison/#:~:text=SimaPro%20SimaPro%20was%20established%2030%20years%20ago%20and,desktop%20software%20as%20well%20as%20a%20cloud-based%20solution..

101. *Estimating the environmental footprint of a grid-connected 20 MWp photovoltaic system.* Szilágyi, A., Gróf, G. s.l. : Solar energy, 2020, Vol. 197.

102. *The greenest decision on photovoltaic system allocation.* Serrano-Lujan et al. s.l. : Renewable Energy, 2017, Vol. 101.

103. *Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels.* Vellini et al. s.l. : Energy, 2017, Vol. 138.

104. International Energy Agency. *National Survey Report of PV Power Applications in Italy 2021.* 2021.

105. *Multi criteria analysis ranking of solar photovoltaic modules manufacturing countries by an importing country: A case of Uganda.* Mukisa et al. 223, s.l. : Solar Energy, 2021.

106. *Using Life Cycle Assessment to Determine the Environmental Impacts Caused by Solar Photovoltaic Systems.* Pal, A., Kilby, J. 2019.

107. *Environmental impacts of large-scale grid-connected ground-mounted PV installations.* Beylot et al. . s.l. : Renewable Energy, 2014, Vol. 61.

108. BP. *bp Statistical Review of World Energy.* 2022.

109. *Life cycle assessment and cost analysis of very-large scale PV systems and suitable locations in the world.* Ito et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2016, Vol. 24.

110. *Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA.* Liu, F., van der Bergh, J. s.l. : Energy Policy, 2020, Vol. 138.

111. *Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China.* Chen et al. s.l. : Journal of Cleaner Production, 2016, Vol. 112.

112. *Energy consumption and carbon footprint of perovskite solar cells.* Carneiro et al. . s.l. : Energy Reports, 2022, Vol. 8.

113. *An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand.* Kittner et al. s.l. : Energy for Sustainable Development, 2013, Vol. 17.

114. *Façade–integrated photovoltaics: a life cycle and performance assessment case study.* Perez et al. . s.l. : Prog. Photovolt: Res. Appl., 2012, Vol. 20.

115. *Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics.* Ng, P., Mithraratne, N. s.l. : Renewable and Sustainable Energy Reviews, 2014, Vol. 31.

116. *A critical review on building integrated photovoltaic products and their applications.* Tripathy et al. s.l. : Renewable and Sustainable Energy Reviews, 2016, Vol. 61.

117. *Life cycle assessment of a floating photovoltaic system and feasibility for application in Thailand.* Clemons et al. s.l. : Renewable Energy, 2021, Vol. 168.

118. *Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment* . Agostini et al. s.l. : Applied Energy , 2021, Vol. 281.

119. *Combined land use of solar infrastructure and agriculture for socioeconomic and environmental co-benefits in the tropics* . Choi et al. . s.l. : Renewable and Sustainable Energy Reviews , 2021, Vol. 151.

120. Agrivoltaics. *Fraunhofer Institute for Solar Energy Systems ISE.* [Online] https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/agrivoltaics.html.

121. *Energy performance of perovskite solar cell fabrication in Argentina. A life cycle assessment approach* . Correa Guerrero et al. . s.l. : Solar Energy , 2021, Vol. 230.

122. *Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV.* Leccisi, E., Fthenakis, V. 2021.

123. *The Embodied Energy Payback Period of Photovoltaic Installations Applied to Buildings in the U.K.* . Wilson, R., Young, A. s.l. : Building and environment, 1996, Vol. 31.

124. *Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options.* Reich et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2011, Vol. 19.

125. *The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update.* Leccisi et al. s.l. : Energies, 2016.

126. *Carbon footprint of polycrystalline photovoltaic systems.* Stylos, N., Koroneos, C. s.l. : Journal of Cleaner Production, 2014, Vol. 64.

127. *Assessment of new functional units for agrivoltaic systems.* Leon, A., Ishihara, K. s.l. : Journal of Environmental Management, 2018, Vol. 226.

128. *Life cycle analysis of organic photovoltaic technologies.* Garcia-Valverde et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2010, Vol. 18.

129. *Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective.* Espinosa et al. s.l. : Solar Energy Materials & Solar Cells, 2015, Vol. 137.

130. *Life cycle assessment of recycling strategies for perovskite photovoltaic modules.* Tian et al. s.l. : Nature Sustainability , 2021, Vol. 4.

131. *The evolution of the dye sensitized solar cells from Grätzel prototype to up-scaled solar applications: A life cycle assessment approach.* Parisi et al. s.l. : Renewable and Sustainable energy reviews, 2014, Vol. 39.

132. *Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China.* Hou et al. . s.l. : Applied Energy, 2016, Vol. 164.

133. *Financial and environmental analysis of rooftop photovoltaic installations with battery storage in Australia.* Nicholls et al. . s.l. : Applied Energy, 2015, Vol. 159.

134. *LCA study of photovoltaic systems based on different technologies.* Soares et al. s.l. : International Journal of Green Energy, 2018.

135. *Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems* . Mehedi et al. . s.l. : Applied Energy , 2022, Vol. 314.

136. *Carrying capacity based environmental impact assessment of Building Integrated Photovoltaics.* Ritzen et al. . s.l. : Sustainable Energy Technologies and Assessments, 2019, Vol. 31.

137. *Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis.* Georgios Martinopoulos. s.l. : Applied Energy, 2020, Vol. 257.

138. *Grid-Connected Semitransparent Building-Integrated Photovoltaic System: The Comprehensive Case Study of the 120kWp Plant in Kunming, China.* Wang et al. . s.l. : International Journal of Photoenergy, 2018.

139. Introduction to RETScreen Expert Software (2 min). *Youtube.* [Online] https://www.youtube.com/watch?v=wa30PZQRGzw.

140. *Life cycle assessment on PERC solar modules* . Jia et al. . s.l. : Solar Energy Materials and Solar Cells , 2021, Vol. 227.

141. *Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China.* Fu et al. . s.l. : Journal of Cleaner Production, 2015, Vol. 86.

142. *Life cycle assessment for photovoltaic integrated shading system with different end of life phases.* Fouad et al. s.l. : International Journal of Sustainable Energy, 2019.

143. *Life-cycle assessment of p-type multi-Si back surface field (BSF) solar module in China of 2019.* Jia et al. . s.l. : Solar Energy, 2020, Vol. 196.

144. *Life cycle assessment of dynamic building integrated photovoltaics.* Jayathissa et al. s.l. : Solar Energy Materials & Solar Cells, 2016, Vol. 156.

145. *Photovoltaics: Life-cycle analyses.* Fthneakis, V., Kim, H. s.l. : Solar energy, 2011.

146. *Environmental performance of window-integrated systems using dye-sensitised solar module technology in Malaysia.* Mustafa et al. s.l. : Solar Energy, 2019, Vol. 187.

147. *Energy payback time and carbon footprint of commercial photovoltaic systems.* de Wild-Scholten, M. s.l. : Solar Energy Materials & Solar Cells, 2013, Vol. 119.

148. NREL. Utility-Scale PV. [Online] https://atb.nrel.gov/electricity/2021/utility-scale_pv.

149. *Should Photovoltaics Stay at Home? Comparative Life Cycle Environmental Assessment on Roof-Mounted and Ground-Mounted Photovoltaics.* Koulompis et al. . s.l. : Sustainability, 2020.

150. *Life-cycle assessment of a photovoltaic system in Catalonia (Spain).* Sumper et al. . s.l. : Renewable and Sustainable Energy Reviews, 2011, Vol. 15.

151. *A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant.* Ito et al. . s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2011, Vol. 19.

152. *Life Cycle Assessment of a ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production systems.* Desideri et al. . s.l. : Applied Energy , 2012, Vol. 97.

153. *LIFE CYCLE ENERGY DEMAND AND GREENHOUSE GAS EMISSIONS FROM AN AMONIX HIGH CONCENTRATOR PHOTOVOLTAIC SYSTEM.* Kim, H., Fthenakis, V. 2006.

154. *Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics.* Ng, P., Mithraratne, N. s.l. : Renewable and Sustainable Energy Reviews, 2014, Vol. 31.

155. *Life cycle assessment of the 3.2 kW cadmium telluride (CdTe) photovoltaic system in composite climate of India.* Rajput et al. . s.l. : Solar Energy, 2018, Vol. 159.

156. *A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies.* Lou et al. . s.l. : Solar Energy Materials and Solar Cells, 2018, Vol. 174.

157. *Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules.* Lunardi et al. . 2018.

158. *Comparison of Environmental Impact Assessment Methods in the Assembly and Operation of Photovoltaic Power Plants: A Systematic Review in the Castilla—La Mancha Region.* Zarzavilla et al. . 2022.

159. *Life cycle analysis of a building integrated photovoltaic system operating in Bogotá, Colombia.* Sierra et al. . 2020.

160. *Eco-Energetical Life Cycle Assessment of Materials and Components of Photovoltaic Power Plant.* Piasecka et al. 2020.

161. *Third generation of photovoltaic panels: A life cycle assessment.* Krebs-Moberg et al. . s.l. : Renewable Energy, 2021, Vol. 164.

162. Licences. *ecoinvent.* [Online] https://ecoinvent.org/offerings/licences/.

163. ecoinvent. *openLCA Nexus.* [Online] https://nexus.openlca.org/database/ecoinvent.

164. *Development of an integrated tool based on life cycle assessment, Levelized energy, and life cycle cost analysis to choose sustainable Facade Integrated Photovoltaic Systems.* Hadi, E., Heidari, A. s.l. : Journal of cleaner production, 2021, Vol. 293.

165. International Energy Agency. *Environmental life cycle assessment of electricity from PV systems.* 2021.

166. *Analysis of the degradation of amorphous silicon-based modules after 11 years of exposure by means of IEC60891:2021 procedure 3.* Piliougine et al. s.l. : Progress in Photovoltaics, 2022.

167. The World Bank. Global Photovoltaic Power Potential By Country. [Online] https://datacatalog.worldbank.org/search/dataset/0038379.

168. ESU Services. *Life Cycle Inventories of Photovoltaics.* 2012.

169. ESU-services. ecoinvent v2.2. [Online] https://esu-services.ch/data/ecoinvent/.

170. *Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies.* Tsang et al. s.l. : Solar Energy Materials & Solar Cells, 2016, Vol. 156.

171. International Energy Agency. *LCI Report .* 2020.

172. *Environmental impacts of solar energy systems: A review.* Rabaia et al. s.l. : Science of the total environment, 2020, Vol. 754.

173. *Ecodesign of organic photovoltaic modules from Danish and Chinese perspectives.* Espinosa Martinez et al. 2022.

174. *Product Environmental Footprint Category Rules (PEFCR): PHOTOVOLTAIC MODULES USED IN PHOTOVOLTAIC POWER SYSTEMS FOR ELECTRICITY GENERATION.* 2019.

175. *Ecoinvent.* [Online] https://v33.ecoquery.ecoinvent.org/Search/Index.

176. *Life cycle analysis of organic photovoltaic technologies.* Garcia-Valverde et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2010, Vol. 18.

177. *Life Cycle Assessment and eco-efficiency of prospective, flexible, tandem organic photovoltaic module.* Hengevoss et al. . s.l. : Solar Energy, 2016, Vol. 137.

178. *A Feasibility Assessment of Photovoltaic Power Systems in Ireland; a Case Study for the Dublin Region.* Murphy, F., McDonnell, K. 2017.

179. Carbon intensity of electricity per kWh. *Our world in data.* [Online] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table&time=earliest..2021.

180. *Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis.* Bhandari et al. s.l. : Renewable and sustainable energy reviews, 2014, Vol. 47.

181. *Energy Pay-Back and Life Cycle CO2 Emissions of the BOS in an Optimized 3.5 MW PV Installation* . Mason et al. . s.l. : Progress in Photovoltaics Research and Applications, 2006.

182. DB. Energy efficiency increased. [Online] https://ibir.deutschebahn.com/ib2018/en/group-management-report/environmental/progress-in-climate-protection/energy-efficiency-increased/.

183. Deutsche Bahn. Facts and figures 2019. [Online] https://www.deutschebahn.com/en/facts_figures-6929196.

184. *Energy intensity in road freight transport of heavy goods vehicles in Spain.* Andres, L., Padilla, E. s.l. : Energy Policy, 2015, Vol. 85.

185. International Energy Agency. *Energy Technology Perspectives 2017.* 2017.

186. Greenhouse gas reporting: conversion factors 2020. *UK.GOV.* [Online] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.

187. *Trade and the greenhouse gas emissions from international freight transport.* Cristea et al. s.l. : Journal of Environmental Economics and Management, 2013, Vol. 65.

188. Stoltz., P., Frischknecht, R., Wyss, F., de Wild-Scholten, M. *PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots.* 2016.

189. *LIFE CYCLE ASSESSMENT OF UTILITY-SCALE CDTE PV BALANCE OF SYSTEMS.* Sinha, P., de Wild-Scholten, M.

190. International Energy Agency. *End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies.* 2018.

191. —. *Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.* 2017.

192. Micromorph solar panels. *Greensolver.* [Online] https://greensolver.net/micromorph-solar-pannels/.

193. *Micromorph and polymorphous solar panel in a warm temperature transitional climate - comparison of outdoor performance and simulations.* Lewinska et al. 2021.

194. *Current-voltage Characteristic Modeling of a Silicon Micromorphous Photovoltaic Module .* Meflah et al. 2015.

195. *The "Micromorph" cell: a new way to high-efficiency-low-temperature crystalline silicon thin-film cell manufacturing?* Keppner et al. 1997.

196. *Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules .* Lim et al. . s.l. : Journal of Cleaner Production , 2022, Vol. 340.

197. *Efficient decommissioning and recycling of polymer solar cells: justification for use of silver.* Søndergaard et al. 2014.

198. *An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment .* Obrecht et al. s.l. : Journal of Cleaner Production , 2021, Vol. 327.

199. *Development of an advanced methodology for assessing the environmental impacts of refurbishments.* Obrecht et al. 2022.

200. *End-of-Life Impact on the Cradle-to-Grave LCA of Light-Duty Commercial Vehicles in Europe.* Accardo et al. 2023.

201. *Harmonization of LCA methodologies for the metal and mining industry.* Santero, N., Hendry, J. 2016.

202. *Circular economy's potential to reduce AAC carbon emissions.* Oliver Kreft. 2022.

203. Market share of the solar PV inverter market worldwide in 2021, based on shipments. *Statista.* [Online] https://www.statista.com/statistics/1003705/global-pv-inverter-market-share-shipments/.

204. SMA plots major solar inverter manufacturing capacity expansion. *PV Tech.* [Online] https://www.pv-tech.org/sma-plots-major-solar-inverter-manufacturing-capacity-expansion/.

205. Solar Mounting System Manufacturers. *ENF Solar.* [Online] https://www.enfsolar.com/directory/component/mounting_system.

206. Sun-age. IMPIANTI FOTOVOLTAICI A TERRA CON UTILIZZO DI BATTIPALO. *Sun-age.* [Online] https://www.sun-age.it/impianti-a-terra/impianti-con-battipalo/.

207. Sunerg solar. [Online] http://www.sunergsolar.com/it/index.php.

208. Tecnikabel. *Tecnikabel.* [Online] https://www.tecnikabel.it/Green_Energy_Cables?1094l1.

209. Enco. Azienda. *Enco.* [Online] https://www.encocavi.it/azienda/.

210. About us. *Grace Solar.* [Online] https://www.gracesolar.com/AboutInfo.html.

211. Canadian Solar. *Investor Presentation December 2022.* 2022.

212. Trina Solar. La nostra azienda. [Online] https://www.trinasolar.com/it/our-company.

213. U.S. Department of Energy. *Solar Photovoltaics Supply Chain Deep Dive Assessment* . 2022.

214. Cable manufacturers. *ENF solar.* [Online] https://www.enfsolar.com/directory/material/cable?page=3.

215. McKinsey & Company. Building a competitive solar-PV supply chain in Europe. [Online] https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/building-a-competitive-solar-pv-supply-chain-in-europe.

216. European Commission. Commission kicks off work on a European Solar Photovoltaic Industry Alliance. [Online] https://commission.europa.eu/news/commission-kicks-work-european-solar-photovoltaic-industry-alliance-2022-10-11_en.

217. Solar Mounting System Manufacturers. *ENF Solar.* [Online] https://www.enfsolar.com/directory/component/mounting_system.

218. Enel . Enel Green Power signs grant agreement with the EU for solar panel gigafactory in Italy. [Online] https://www.enel.com/media/explore/search-press-releases/press/2022/04/enel-green-power-signs-grant-agreement-with-the-eu-for-solar-panel-gigafactory-in-italy.

219. *Searates.* [Online] https://www.searates.com/services/distances-time/.

220. GSE. *Rapporto statistico Solare fotovoltaico 2021.* 2022.

221. International Energy Agency. *Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.* 2017.

222. U.S. solar panel manufacturers. *Solar Power World.* [Online] https://www.solarpowerworldonline.com/u-s-solar-panel-manufacturers/.

223. 13 Major Ports in China. *Maritime manual.* [Online] https://www.maritimemanual.com/major-ports-in-china/.

224. Top 15 Ports in Italy. *Maritime manual.* [Online] https://www.maritimemanual.com/ports-in-italy/#:~:text=Top%2015%20Ports%20in%20Italy%201%201%29%20Port,port%20in%20Messina%2C%20Sicily%2C%20Italy.%20...%20Altri%20elementi.

225. *Google Maps.* [Online] https://www.google.com/maps/dir/Cassano+d'Adda/Porto+di+Trieste,+Trieste,+TS/@45.6122555,10.5221929,267044m/data=!3m1!1e3!4m14!4m13!1m5!1m1!1s0x47814aec63453f07:0xfd8b86b9e19c60b7!2m2!1d9.5140979!2d45.526634!1m5!1m1!1s0x477b6b79d466d8e7:0x48196f16e80e572f.

226. *Google Maps.* [Online] https://www.google.com/maps/dir/Cassano+d'Adda,+20062+MI/Sonnenallee+1,+34266+Niestetal,+Germania/@48.3364786,4.4044708,6z/data=!3m1!4b1!4m14!4m13!1m5!1m1!1s0x47814aec63453f07:0xfd8b86b9e19c60b7!2m2!1d9.5140979!2d45.526634!1m5!1m1!1s0x47bb388d4794e74b:0x8.

227. Fraunhofer Institute. *Aktuelle Fakten zur Photovoltaik in Deutschland.* 2022.

228. Meyer Burger opens high tech module factory in Freiberg, Germany. *Meyer Burger.* [Online] https://www.meyerburger.com/it/newsroom/artikel/meyer-burger-opens-high-tech-module-factory-in-freiberg-germany.

229. FIMER. FIMER becomes the 4th largest solar inverter suppliers in the world. [Online] https://www.fimer.com/fimer-becomes-4th-largest-solar-inverter-suppliers-world.

230. Company Profile. *fimer.* [Online] https://www.fimer.com/system/files/2021-07/FIMER_Company_Profile__IT_Rev_B.pdf.

231. *Cumulative energy demand and cumulative emissions of photovoltaics production in Europe.* Gurzenich, D., Wagner, H. s.l. : Energy, 2004, Vol. 29.

232. *Life-cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains.* Dones, R., Frischknecht, R. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 1998, Vol. 6.

233. *Comparative life-cycle energy payback analysis of multi-junction a-SiGe and nanocrystalline/a-Si modules.* Kim, H., Fthenakis, V. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2010, Vol. 19.

234. ENEA. Solaritaly | Table values of Solar Radiation in Italy. *ENEA.* [Online] http://www.solaritaly.enea.it/TabelleRad/TabelleRadIt.php.

235. ISPRA. LCA. *isprambiente.gov.* [Online] https://www.isprambiente.gov.it/it/attivita/certificazioni/ipp/lca.

236. Integrated product policy. *EUR-LEx.* [Online] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al28011&lang1=EN&from=IT&lang3=choose&lang2=choose&_csrf=c3ce0ea1-1e56-40ab-a1d9-d2df347a37f0.

237. Commission, European. COMUNICAZIONE DELLA COMMISSIONE AL CONSIGLIO E AL PARLAMENTO EUROPEO: Politica integrata dei prodotti: Sviluppare il concetto di ciclo di vita ambientale. *Registro dei documenti della Commissione.* [Online] https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2003)302&lang=it.

238. Golsteijn, Laura. Life Cycle Assessment (LCA) explained. *pre-sustainability.* [Online] 2020. https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/.

239. Life Cycle Assessment. *ScienceDirect.* [Online] 2017. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/life-cycle-assessment.

240. What is life cycle assessment (LCA)? *Rochester Institute of Technology.* [Online] https://www.rit.edu/sustainabilityinstitute/blog/what-life-cycle-assessment-lca.

241. International Energy Agency. *World Energy Outlook 2021.* 2021.

242. —. *Net Zero by 2050.* 2021.

243. Bloomberg New Energy Finance. Scale-up of Solar and Wind Puts Existing Coal, Gas at Risk. *BloombergNEF.* [Online] https://about.bnef.com/blog/scale-up-of-solar-and-wind-puts-existing-coal-gas-at-risk/.

244. Lazard. *Levelized Cost of Energy Report.* 2020.

245. Management of Energy course notes, Prof. Simone Franzo'. 2021-2022.

246. International Energy Agency. Tracking Power 2021. [Online] https://www.iea.org/reports/tracking-power-2021.

247. Electricity prices. *Global Petrol Prices.com.* [Online] https://www.globalpetrolprices.com/electricity_prices/.

248. Franzo', Simone. Management of Energy Course Slides, Prof. Simone Franzo', Academic Year 2021-2022.

249. MInistero della Transizione Ecologica. WORKSHOP PER LE PUBBLICHE AMMINISTRAZIONI SU LCA E VALUTAZIONE DELL'IMPRONTA AMBIENTALE. *Mettiamoci in riga.* [Online] https://mettiamociinriga.mite.gov.it/component/icagenda/event?id=117.

250. ISO. ISO 14045:2012. *ISO.* [Online] https://www.iso.org/standard/43262.html#:~:text=ISO%2014045%3A2012%20Environmental%20management%20%E2%80%94%20Eco-efficiency%20assessment%20of,standard%20was%20last%20reviewed%20and%20confirmed%20in%202019..

251. —. ISO 14046:2014. *ISO.* [Online] https://www.iso.org/standard/43263.html.

252. —. ISO/TR 14047:2012. *ISO.* [Online] https://www.iso.org/standard/57109.html.

253. —. ISO/TS 14048:2002. *ISO.* [Online] https://www.iso.org/standard/29872.html.

254. —. ISO/TR 14049:2012. *ISO.* [Online] https://www.iso.org/standard/57110.html.

255. PV*SOL online - a free tool for solar power (PV) systems. *PV SOL.* [Online] http://pvsol-online.valentin-software.com/#/.

256. Calsol. *INES Education - Logiciel CALSOL - Gisement solaire.* [Online] https://outils-numeriques.ines-solaire.org/calsol/gisesol_1.php.

257. Alternative, European. TCO calculator. *European Alternative Fuels Observatory.* [Online] https://www.eafo.eu/knowledge-center/tco-calculator.

258. European Environment Agency. Specific CO2 emissions per tonne-km and per mode of transport in Europe. [Online] https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-chart_1.

259. International Energy Agency. *Railway Handbook.* 2012.

260. FluxPower. What is the Energy Density of a Lithium-Ion Battery? [Online] https://www.fluxpower.com/blog/what-is-the-energy-density-of-a-lithium-ion-battery.

261. Lazard. *LAZARD'S LEVELIZED COST OF STORAGE ANALYSIS—VERSION 7.0.* 2021.

262. IRENA. *Electricity storage costs.* 2017.

263. *Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation.* Hsu et al. s.l. : Journal of industrial ecology, 2012.

264. *Ecodesign of photovoltaic grid-connected systems.* Gallardo et al. s.l. : Renewable energy, 2013, Vol. 64.

265. *Life cycle assessment of solar PV based electricity generation systems: A review.* Sherwani et al. s.l. : Renewable and Sustainable Energy Reviews, 2009, Vol. 14.

266. *Review of the Life Cycle Greenhouse Gas Emissions from Different Photovoltaic and Concentrating Solar Power Electricity Generation Systems.* Raghava et al. . s.l. : Energies, 2016.

267. *Life Cycle Analysis of Solar PV System: A Review.* Baharwani et al. s.l. : International Journal of Environmental Research and Development., 2014.

268. OET. Organic Photovoltaic Panels: Product datasheet. [Online] https://oe-technologies.com/wp-content/uploads/flyers/oet_apollo_opv_datasheet.pdf.

269. Enel Green Power. Energy Storage Systems, Presentation by Francesco Sala, 6th April 2022. 2022.

270. IRENA. *END-OF-LIFE MANAGEMENT: SOLAR PHOTOVOLTAIC PANELS.* 2016.

271. Energy & Strategy Group. *Tecnologie emergenti: tecnologie fotovoltaiche.*

272. *Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs.* Louwen et al. s.l. : Progress in Photovoltaics, 2014, Vol. 23.

273. HELIENE. 66M HJT All Black Module. [Online] https://heliene.com/wp-content/uploads/documents/SpecSheets/HSPE_66M_M2+_HJT_REV.06.pdf.

274. *LIFE CYCLE ASSESSMENT OF HETEROJUNCTION SOLAR CELLS AND MODULES* . Olson et al. 2011.

275. *Geospatial analysis of the energy yield and environmental footprint of different photovoltaic module technologies.* Louwen et al. . 2017.

276. *Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system.* Grejer et al. s.l. : Renewable energy, 2000, Vol. 23.

277. *Flexible high power-per-weight perovskite solar cells with chromium oxide–metal contacts for improved stability in air.* Kaltenbrunner et al. 2015.

278. perovskite photovoltaics get their groove on. *Chemistry World.* [Online] https://www.chemistryworld.com/news/perovskite-photovoltaics-get-their-groove-on-/3010516.article.

279. Top 10 Leading Mounting Structure Companies in India. *Loom Solar.* [Online] https://www.loomsolar.com/blogs/reviews/list-of-top-10-leading-mounting-structure-companies-in-india#:~:text=Mounting%20structures%20are%20the%20backbone,they%20receive%20maximum%20solar%20irradiation..

280. Grid Connected Photovoltaic Systems. *Science Direct.* [Online] https://www.sciencedirect.com/topics/engineering/grid-connected-photovoltaic-systems.

281. IRENA. *Renewable Energy and Jobs Annual Review 2021.* 2021.

282. Lazard. *LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS — VERSION 15.0.* 2021.

283. IRENA. *RENEWABLE POWER GENERATION COSTS IN 2021.* 2022.

284. UNEP. *GUIDELINES FOR SOCIAL LIFE CYCLE ASSESSMENT OF PRODUCTS.* 2009.

285. GreenDelta GmbH. Life Cycle Sustainability Assessment of photovoltaic panels using soca. 2017.

286. *Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria.* Akinyele et al. . s.l. : Renewable energy , 2017, Vol. 101.

287. *Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective.* Espinosa et al. . s.l. : Solar Energy Materials & Solar Cells, 2015, Vol. 137.

288. *Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab.* Celik et al. s.l. : Solar Energy Materials & Solar Cells, 2016, Vol. 156.

289. ReCiPe. *Gabi Solutions.* [Online] https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/recipe/#:~:text=The%20ReCiPe%20LCA%20methodology%20was%20created%20by%20RIVM%2C,of%20the%20CML%202001%20and%20Ecoindicator%2099%20methodologies..

290. *Life cycle analysis of organiz photovoltaics: a review.* Lizin et al. s.l. : Energy & environmental science, 2013.

291. IRENA. *Renewable Energy and Jobs Annual Review 2022.* 2022.

292. CML 2001. *sphera.* [Online] https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/cml-2001/.

293. *Integrated agricultural and dairy production within a circular economy framework. A comparison of Italian and Polish farming systems.* Ghisellini et al. s.l. : Integrated agricultural and dairy production within a circular economy framework. A comparison of Italian and Polish farming systems, 2014, Vol. 2.

294. *Location and technology options to reduce environmental impacts.* Page et al. . s.l. : Journal of Cleaner Production, 2014, Vol. 81.

295. *Life cycle assessment of pasture-based agrivoltaic systems: Emissions and energy use of integrated rabbit production.* Pascaris et al. . s.l. : Cleaner and Responsible Consumption, 2021, Vol. 3.

296. *Life cycle environmental impacts from CZTS (copper zinc tin sulfide) and Zn3P2 (zinc phosphide) thin film PV (photovoltaic) cells.* Collier et al. . s.l. : Energy, 2014, Vol. 74.

297. Licenses. *SimaPro.* [Online] https://simapro.com/licences/#/business.

298. US Energy Information Administration. Solar plants typically install more panel capacity relative to their inverter capacity. [Online] https://www.eia.gov/todayinenergy/detail.php?id=35372.

299. *Life Cycle Inventory and Assessment of different Solar Photovoltaic Systems .* Baharwani et al. . 2014.

300. OEM Specialist – lavoro conto terzi. *Eclipse Italia.* [Online] https://www.eclipseitalia.com/lavoro-conto-terzi-per-la-produzione-di-moduli-fotovoltaici/.

301. Peimar. *Company presentation.*

302. Top 10 Busiest India Ports. *cogoport.* [Online] https://www.cogoport.com/en-IN/blogs/top-10-busiest-india-ports.

303. 10 major ports in Brazil. *marine insights.* [Online] https://www.marineinsight.com/know-more/10-major-ports-in-brazil/.

304. Top 10 largest seaports in Vietnam. *LEC Vietnam.* [Online] https://lecvietnam.com/en/operations/community-information/top-10-largest-seaports-in-vietnam-111.html.

305. *Google Maps.* [Online] https://www.google.it/maps/dir/Berlin,+Germania/Milano,+MI/@47.9726767,6.4772549,5.75z/data=!4m14!4m13!1m5!1m1!1s0x47a84e373f035901:0x42120465b5e3b70!2m2!1d13.404954!2d52.5200066!1m5!1m1!1s0x4786c1493f1275e7:0x3cffcd13c6740e8d!2m2!1d9.189982!2d45.4642035!.

306. *Greenhouse Gas Emissions from Intra-National Freight Transport: Measurement and Scenarios for Greater Sustainability in Spain* . Llano et al. 2018.

307. NREL. Champion Photovoltaic Module Efficiency Chart. [Online] https://www.nrel.gov/pv/module-efficiency.html.

308. *Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems.* Wong et al. s.l. : Renewable and Sustainable Energy Reviews, 2016, Vol. 58.

309. *Life cycle assessment of multicrystalline silicon photovoltaic cell production in China.* Hong et al. s.l. : Solar energy, 2016, Vol. 133.

310. International Energy Agency. Power carbon intensity in key regions in the Stated Policies Scenario, 2000-2040. [Online] https://www.iea.org/data-and-statistics/charts/power-carbon-intensity-in-key-regions-in-the-stated-policies-scenario-2000-2040.

311. Seven countries with the dirtiest electricity in 2030 will undermine eu climate goals. *Sonnenseite.* [Online] https://www.sonnenseite.com/en/politics/seven-countries-with-the-dirtiest-electricity-in-2030will-undermine-eu-climate-goals/.

312. DNV. Solar PV powering through to 2030. [Online] https://www.dnv.com/to2030/technology/solar-pv-powering-through-to-2030.html.

313. *IPVF's PV technology vision for 2030.* Oberbeck et al. . 2020.

314. EGEB: 7 countries could cause the EU to miss emissions targets . *Tesla news.* [Online] https://www.teslanews.co.uk/egeb-7-countries-could-cause-the-eu-to-miss-emissions-targets/.

315. TERNA. *L'ELETTRICITA' NELLE REGIONI.* 2021.

316. International Energy Agency. Power generation, export and electricity demand in Xinjiang province, 2019. [Online] https://prod.iea.org/data-and-statistics/charts/power-generation-export-and-electricity-demand-in-xinjiang-province-2019.

317. Explainer: The power crunch in China's Sichuan and why it matters. *Reuters.* [Online] https://www.reuters.com/world/china/power-crunch-chinas-sichuan-why-it-matters-2022-08-26/#:~:text=Hydropower%20is%20the%20biggest%20source%20of%20electricity%20supply,to%20maximise%20output%20to%20meet%20peak%20summer%20demand..

318. China's Qinghai generates more electricity using clean energy in 2020. *Global Times.* [Online] https://www.globaltimes.cn/page/202102/1214678.shtml.

319. *China's electricity emission intensity in 2020 – an analysis at provincial level.* Li et al. . 2017.

320. insulated wire exports country. *World top exports.* [Online] https://www.worldstopexports.com/insulated-wire-exports-country/.

321. Largest US solar manufacturer to double its production with a new factory. *electrek.* [Online] https://electrek.co/2021/06/09/largest-us-solar-manufacturer-to-double-its-production-with-a-new-factory/.

322. Maximum production capacity of solar photovoltaic cells and modules in Italy in 2020, by manufacturer. *Statista.* [Online] https://www.statista.com/statistics/945933/maximum-production-capacity-of-photovoltaic-modules-in-italy/#:~:text=Published%20by%20Statista%20Research%20Department%2C%20Aug%201%2C%202022,in%202020%2C%20by%20manufacturer%20%28in%20megawatts%20per%20year%29.

323. *Life Cycle Analysis of Solar Module Recycling Process .* Muller et al. . 2006.

324. Global Inverter Manufacturing Locations. *Solar Power World.* [Online] https://www.solarpowerworldonline.com/global-inverter-manufacturing-locations/.

325. Italian Cable Company. Company. *Italian Cable Company.* [Online] https://icc.it/en/company/.

326. A+ Sun Systems. [Online] http://www.apsunsys.com/.

327. *Socio-Economic and Environmental Impacts of Silicon Based Photovoltaic (PV) Technologies.* Dubey et al. 2013.

328. *Systematic literature review on the application of life cycle sustainability assessment in the energy sector.* Dantas T., Soares S. 2021.

329. *Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems.* Kim et al. s.l. : Solar Energy, 2014, Vol. 103.

330. *Environmental Impact of Crystalline Silicon Photovoltaic Module Production.* Alsema, E., de Wild Scholten, M. 2005.

331. *Parameters affecting the life cycle performance of PV technologies and systems.* Pacca et al. s.l. : Energy Policy, 2007, Vol. 35.

332. *ENVI-PV: an interactive Web Client for multi-criteria life cycle assessment of photovoltaic systems worldwide.* Perez Lopez et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2016, Vol. 25.

333. *A model for estimating life cycle environmental impacts of offshore wind electricity considering specific characteristics of wind farms.* Koulompis, V., Azapagic, A. 2021.

334. *Crystalline Silicon vs. Amorphous Silicon: the Significance of Structural Differences in Photovoltaic Applications.* Kang, H. 2021.

335. *Energy, Cost and LCA Results of PV and Hybrid PV/T Solar Systems.* Tripanagnostopoulos et al. s.l. : PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 2005, Vol. 13.

336. *Cumulative energy demand for small molecule and polymer photovoltaics.* Anctil et al. s.l. : Progress in Photovoltaics, 2012, Vol. 21.

337. *Large scale deployment of polymer solar cells on land, on sea and in the air.* Espinosa et al. s.l. : Energy & Environmental Science, 2014.

338. *The environmental impact of Li-Ion batteries and the role of key parameters.* Peters et al. s.l. : Renewable and Sustainable Energy Reviews, 2015, Vol. 67.

339. *Comparative Life Cycle Assessment of Merging Recycling Methods for Spent Lithium Ion Batteries.* Zhou et al. s.l. : Energies, 2021.

340. *Supplemental information: Projecting the Future Levelized Cost of Storage.* Schmidt et al. 2019 : Joule, Vol. 3.

341. Ito, M. Life Cycle Assessment of PV systems. *Crystalline silicon - Properties and uses.* 2010.

342. *LIFE CYCLE ASSESSMENT OF GRATZEL-TYPE CELL PRODUCTION FOR NON CONVENTIONAL PHOTOVOLTAICS FROM NOVEL ORGANIC DYES.* Parisi et al. 2011.

343. *Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts.* Gong et al. 2015.

344. *Economic and environmental analysis of a residential PV system: A profitable contribution to the Paris agreement.* Arcos-Vargas et al. 2018.

345. *Environmental Impacts of Photovoltaics: The Effects of Technological Improvements and Transfer of Manufacturing from Europe to China.* Stamford., L., Azapagic, A. 2018.

346. *Influence of allocation methods on the LC-CO2 emission of an agrivoltaic system.* Leon, A., Ishihara, K. s.l. : Resources, Conservation & Recycling, 2018, Vol. 138.

347. GSE. *Rapporto Statistico 2020: Energia da fonti rinnovabili in Italia.* 2022.

348. *A cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems.* de Wild-Scholten et al. 2006.

349. *A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration.* Kebede et al. s.l. : Renewable and sustainable energy reviews, 2022, Vol. 159.

Appendix

Appendix A.1: Literature review table

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
1	Rashedi et Khanam	2020	Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method	Journal article	1 kW	ecoinvent 3.1; literature	yes	secondary data	2014	Recipe	no	no	no	no	yes	yes	yes	yes	yes	yes
2	Hou et al.	2016	Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China	Journal article	not specified	literature , field visits , industry data	yes	primary and secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
3	Yu et al.	2017	Life cycle assessment of grid-connected power generation from metallurgical route multi-crystalline silicon photovoltaic system in China	Journal article	1 MW PV plant	industry data, literature; ecoinvent; Chinese Life Cycle Database (CLCD) v0.8	yes	primary and secondary data	2013	not specified	no	yes	no	yes	yes	yes	yes	yes	yes	yes
4	Kim et al.	2014	Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems	Journal article	1 kWh	field visits; industry data; ecoinvent	yes	primary and secondary data	n/a	not specified	yes	yes	yes	no	yes	yes	yes	yes	yes	no
5	Rahman et al.	2019	A life cycle assessment model for quantification of environmental footprints of a 3.6 kWp photovoltaic system in Bangladesh	Journal article	1 kWh	literature	no	secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	yes	no	no	no
6	Fthenakis and Kim	2011	Photovoltaics: Life-cycle analyses	Journal article	not specified	literature	no	secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
7	Santoli et al.	2010	Life cycle assessment of electricity generated by photovoltaic systems manufactured in Europe and installed in buildings in the city of Rome	Journal article	1 kWh	industry data	no	primary data	n/a	not specified	no	no	no	no	yes	yes	no	yes	yes	yes
8	Szilágyi and Gróf	2020	Estimating the environmental footprint of a grid-connected 20 MWp photovoltaic system	Journal article	1 kWh	industry data; ecoinvent	yes	primary and secondary data	2018	ILCD 1.08 product environmental footprint (PEF)	no	no	no	no	yes	yes	yes	yes	yes	yes
9	Nordin et al.	2020	Life-cycle assessment of residential-scale grid-connected photovoltaic system in malaysia based on monocrystalline silicon modules	Journal article	1 kWh	ecoinvent 3.5; literature	yes	secondary data	2018	IMPACT2002+	yes	yes	no	yes	yes	yes	yes	yes	yes	no
10	Beylot et al.	2014	Environmental impacts of large-scale grid-connected ground-mounted PV installations	Journal article	1 kWh	ecoinvent 2.0 (2007); industry data; Literature	yes	primary and secondary data	2007	IMPACT 2002	yes	no	no	yes	yes	yes	yes	yes	yes	yes

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/ combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/ agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
1	yes	Simapro 8.0	no	no	not applicable	EU	not specified	not specified	EU	1; 2	mono-Si, multi-Si, a-Si, CdTe	rooftop	not applicable	no	not specified	not specified	30	15 inverter
2	no	not applicable	yes	yes	irradiation	China	not specified	not specified	China	1	mono-si, multi-si	Ground mounted	not applicable	no	17% mono cells	<3780 to >6300 MJ/m2	25	10 to 15 inverter
3	yes	eBalance v4.7	no	no	not applicable	China	China	same	China	1	multi-si	Ground mounted	not applicable	No	14% multi modules	not specified	30	10 to 15 inverter
4	not specified	not specified	not specified	no	not applicable	malaysia	Malaysia	same	malaysia	1; 2	cdte; mono-si, multi-si, ribbon, CIS, a-Si	Ground mounted	not applicable	No	11.2% CDTE module	1810 kWh/m2*year	30	not specified
5	no	not applicable	yes	yes	days of autonomy, depth of discharge of battery, irradiation, and module efficiency	germany	Bangladesh	different	bangladesh	1	multi-si	Not specified	not applicable	Yes	13% multi module	4.8 kWh/m2*day	20	10 inverter
6	not specified	not specified	not specified	no	not applicable	EU; USA	not specified	not specified	EU; USA	1; 2	Mono-si, multi-si, a-Si, Cdte, Ribbon silicon	rooftop	not applicable	No	ribbon 11,5%; multi 13.2 %; mono 14% modules	1700 and 1800 kWh/m2*year	30	not specified
7	not specified	not specified	not specified	no	not applicable	EU	not applicable	not applicable	Italy	1	multi-si	rooftop	not applicable	No	12.5% multi module	1737 Wh/m2	25	not applicable
8	no	not applicable	yes	no	not applicable	not specified	not specified	not specified	Hungary	1	multi-si	Ground mounted	not applicable	No	16.5% multi module	1200 kWh/m2*year	25	10 inverter
9	yes	OpenLCA 1.8	no	yes	lifetime; irradiation	Germany	not specified	not specified	Malaysia	1	mono-si	rooftop	not applicable	no	14% mono module	1561 kWh/m2*year	21	15 inverter
10	not specified	not specified	not specified	no	not applicable	not specified	not specified	not specified	not specified	1	multi-si	Ground mounted	not applicable	no	14% multi modules	1700 kWh/m2*year	30	10 inverter

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
11	Raugei et al.	2020	What Are the Energy and Environmental Impacts of Adding Battery Storage to Photovoltaics? A Generalized Life Cycle Assessment	Journal article	1 kWh	literature; ecoinvent	yes	secondary data	2018	CML	yes	yes	no	yes	yes	yes	yes	yes	yes	no
12	Liu et al.	2020	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	Journal article	not specified	literature	no	secondary data	n/a	not specified	no	no	no	yes	yes	yes	yes	yes	yes	yes
13	Luo et al.	2018	A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies	Journal article	one 60-cell silicon PV module	data from pilot production line; ecoinvent 3.3; literature	yes	primary and secondary data	2016	not specified	yes	yes	no	yes	yes	yes	yes	yes	no	no
14	Piasecka et al.	2020	Eco-energetical life cycle assessment of materials and components of photovoltaic power plant	Journal article	1000 MWh of electricity	Simapro database; industry data	yes	primary and secondary data	n/a	Eco-indicator 99	no	no	no	yes	yes	no	yes	yes	yes	yes
15	Desideri et al.	2012	Life Cycle Assessment of a ground-mounted 1778kWp photovoltaic plant and comparison with traditional energy production systems	Journal article	1 kWh	Ecoinvent; field visit; industry data	yes	primary and secondary data	2007	Eco-indicator '99.	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
16	Kim et al.	2014	Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea	Journal article	1 kWh	Ecoinvent; literature; industry data	yes	primary and secondary data	2007	not specified	yes	yes	yes	No	yes	not specified	yes	yes	yes	yes
17	Koulompis et al.	2020	Should photovoltaics stay at home? Comparative life cycle environmental assessment on roof-mounted and ground-mounted photovoltaics	Journal article	1 kWh	Ecoinvent 3.5 database (2018); Data from plants	yes	primary and secondary data	2018	CML 2001	no	no	no	no	yes	yes	yes	yes	yes	no
18	Antonanzas et al.	2019	Comparative life cycle assessment of fixed and single axis tracking systems for photovoltaics	Journal article	1 kW	literature; ecoinvent	yes	secondary data	2014	Recipe	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
19	Üçtuğ and Azapagic	2018	Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries	Journal article	1 kWh	Ecoinvent 2.2; literature; industry data	yes	primary and secondary data	2010	CML 2001	yes	no	no	no	yes	yes	yes	yes	yes	yes
20	de Wild-Scholten	2013	Energy payback time and carbon footprint of commercial photovoltaic systems	Journal article	not specified	Ecoinvent; industry data; literature	yes	primary and secondary data	2010	not specified	yes	yes	no	no	yes	not specified	yes	no	no	no
21	Santoyo-Castelazo et al.	2021	Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: A case study for Mexico	Journal article	1 kWh	Ecoinvent; Literature; industry data	yes	primary and secondary data	2014	CML 2001	no	no	no	no	yes	yes	yes	yes	yes	yes
22	Pamponet et al.	2021	Energy balance and carbon footprint of very large-scale photovoltaic power plant	Journal article	1 kWh	ecoinvent	no	secondary data	2018	ReCiPe 2016	yes	yes	no	no	yes	yes	yes	yes	yes	no
23	Leccisi et al.	2016	The energy and environmental performance of ground-mounted photovoltaic systems - A timely update	Journal article	not specified	Ecoinvent; industry data; literature	yes	primary and secondary data	2014	CML method: GWP, Ozone depletion potential, acidification potential, photochemical ozone creation potential, abiotic depletion potential, ecotoxicity, eutrophication,	yes	yes	no	yes	yes	yes	yes	yes	not specified	no
24	Laleman et al,	2011	Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation	Review	not applicable	Ecoinvent	no	secondary data	2007	Eco-Indicator 99	yes	yes	no	yes	not specified	not specified	not specified	not specified	not specified	not specified
25	Mehedi et al.	2022	Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems	Journal article	1 kWh	industry data; literature	yes	primary and secondary data	n/a	not specified	yes	yes	no	no	yes	yes	yes	yes	yes	yes
26	Bayod-Rújula et al.	2011	Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems	Journal article	1 kWh	Ecoinvent; industry data	yes	primary and secondary data	n/a	eco indicator 99	no	yes	yes	no	yes	yes	yes	yes	no	yes
27	Ito et al.	2011	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant	Journal article	not specified	NEDO database; data from real system	yes	primary and secondary data	n/a	eco indicator 99	yes	yes	no	yes	yes	yes	yes	yes	no	yes
28	Stylos and Koroneos	2014	Carbon footprint of polycrystalline photovoltaic systems	Journal article	1 kWh	Ecoinvent 2.0; literature	yes	secondary data	2007	Eco-Indicator '95	yes	no	no	yes	yes	yes	yes	yes	no	no
29	Nordin et al.	2022	Energy and environmental impacts of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: A life-cycle approach	Journal article	1 kWh	industry data, manufacturers, field visit, literature	yes	primary and secondary data	n/a	recipe 2016	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
30	Fthenakis and Leccisi	2021	Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends	Journal article	1 kW	Ecoinvent v3; literature	yes	secondary data	n/a	CML method: GWP, Ozone depletion potential, acidification potential, photochemical ozone creation potential, abiotic depletion potential, ecotoxicity, eutrophication,	yes	yes	no	yes	yes	yes	yes	yes	yes	no

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/ combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/ agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
11	not specified	not specified	not specified	yes	irradiation	China	Battery in China	combination	not specified	1	mono-si, multi-si	Ground mounted	not applicable	Yes	16.7% multi; 18% mono modules	1000; 1700; 2300 kWh/m2*year	30	not specified
12	not specified	not specified	not specified	yes	irradition; lifetime	China; EU; USA	China; EU; USA	same	China; EU; USA	1; 2	mono-Si, multi-Si, a-Si, CdTe and CIS	both	not applicable	no	mono 17%; multi 14%; cdTe 10%; CIS 11%; aSi 7.5% not specified if cell or module	1200-2000 kWh/m2*year	30	not specified
13	not specified	not specified	not specified	no	not applicable	Singapore	not specified	not specified	Singapore	1	multi-si	rooftop	not applicable	no	15.9 - 16.7 % multi module BSF and PERC technology	1580 kW/m2*year	25 and 30	not specified
14	yes	simapro 8.4	no	no	not applicable	EU	not specified	not specified	Poland	1	multi-si	Ground mounted	not applicable	no	not specified	not specified	20	not specified
15	yes	simapro 7.1	no	no	not applicable	China	not specified	not specified	Italy	1	multi-si	Ground mounted	not applicable	no	not specified	not specified	25	not specified
16	yes	simapro 7.1	no	yes	irradiation; module efficiency	Korea	Korea	same	Korea	1	mono-si, multi-si	Ground mounted	not applicable	no	15.96 mono; 14.91 multi modules	1310 kWh/m2*year	30	not specified
17	yes	gabi 9.2	no	yes	distance from point of connection to grid	not specified	not specified	not specified	Greece	1	multi-si	both	not applicable	no	not specified	not specified	30	15 inverter
18	yes	openLCA 1.7.4	no	no	not applicable	China	China	same	Eu; USA; China	1	multi-si	Ground mounted	not applicable	no	17.5% multi modules	948 to 2327 kWh/ m2*year	30	not specified
19	yes	CCalC	no	no	not applicable	China	Inverter Turkey; Battery Germany	different	Turkey	1	multi-si	rooftop	not applicable	Yes	not specified	not specified	25	10 battery
20	yes	simapro 7.3.3	no	no	not applicable	China; EU	China and EU	same	not applicable	1; 2	mono-si, multi-si, a-Si, Cdte, micromorpoh silicon, CIGS	rooftop	not applicable	no	mono 14.8; multi 14.1; aSi 7; cdte 11.9; CIGS 11.7 modules	1700 kWh/m2*year	30	not specified
21	yes	gabi v.6	no	no	not applicable	not specified	not specified	not specified	Mexico	1; 2	multi-si; a-Si, CIS; mono-si	rooftop	not applicable	no	14.7 multi module	1156 kWh/kW	30	not specified
22	yes	simapro v8.5.2	no	no	not applicable	Brazil; China	Brazil or China	same	Brazil	1	mono-si, multi-si	Ground mounted	not applicable	no	16.75% multi module	4700 to 5300 Wh/m2	30	not specified
23	yes	simapro 8	no	yes	irradiation	EU; USA; China; Japan; malaysia	EU; US; China	same	not specified	1; 2	mono-Si , multi-Si, CdTe, and CIGS	Ground mounted	not applicable	no	mono 17; multi 16; cdte 15.6; CIGS 14 not specified if cell or module	1000; 1700; 2300 kWh/m2*year	30	not specified
24	not specified	not specified	not specified	no	not applicabel	not specified	not applicable	not applicable	Belgium	1; 2	CdTe, CIS, ribbon si, multi-Si, mono-Si, a-Si	rooftop	not applicable	no	mono 14; multi 13; aSI 7; CIS 10; cdte 10 module	900 - 1000 kWh/m2*year	20; 30	not specified
25	not specified	not specified	not specified	yes	orientations	not specified	Inverters Canada; Batteries USA	not applicable	Canada	1	multi-si	Ground mounted	not applicable	Yes	16.72% multi module	186 kWh/m2*month	25	10 inverter
26	yes	simapro	no	yes	location	not specified	Germany and Spain inverters	not applicable	Germany; Spain	1	mono-si, multi-si	Not specified	not applicable	no	13.1% multi module	4619; 5980 Wh/m2*day	25	not specified
27	yes	JEMAI-LCA	no	no	not applicabel	Japan	Japan	same	Japan	1; 2	mono-si, a-Si, multi-si, CIS	Ground mounted	not applicable	no	mono 14.3; multi 13.9; aSi 8.6; CIS 10.1 module	1725 kWh/m2*year	30	not specified
28	yes	gabi	no	no	not applicabel	Japan	Germany	different	Greece	1	multi-si	Ground mounted	not applicable	Yes	14; 17; 20% multi cell	1797 kWh/m2*year	20; 40; 50	10 batteries
29	yes	simapro v9	no	yes	irradiation; PR; lifetime	Malaysia	Malaysia	same	Malaysia	1	multi-si	Ground mounted	not applicable	No	17.1% multi module	1958 kWh/m2*year	30	not specified
30	yes	simapro 9	no	yes	irradiation; grid efficiency	China	China	same	not specified	1	mono-SI; multi-Si	ground mounted	not applicable	no	20,5 sc-Si; 18 mc-Si modules	1000; 1700; 2300 kWh/m2*year	30	not specified

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
31	Akinyele	2017	Environmental performance evaluation of a grid-independent solar photovoltaic power generation (SPPG) plant	Journal article	not specified	literature	no	secondary data	n/a	not specified	no	yes	no	yes	yes	yes	yes	yes	yes	yes
32	Akinyele et al.	2017	Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria	Journal article	not specified	literature	no	secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	no	yes	yes	yes
33	Baharwanj et al.	2014	Life cycle inventory and assessment of different solar photovoltaic systems	Conference paper	not applicable	not applicable	not applicable	n/a	n/a	not specified	yes	yes	no	yes	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
34	Sumper et al.	2011	Life-cycle assessment of a photovoltaic system in Catalonia (Spain)	Review	not applicable	industry data; Simapro database	yes	primary and secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	yes	yes	no	no
35	Ludin et al.	2018	Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review	Review	not applicable	not applicable	not applicable	n/a	n/a	not specified	yes	yes	no	yes	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
36	Muteri et al.	2020	Review on life cycle assessment of solar photovoltaic panels	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
37	Chatzisideris et al.	2016	Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies	Journal article	not applicable	not applicable	not applicable	n/a	n/a	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
38	Shewani et al.	2010	Life cycle assessment of solar PV based electricity generation systems: A review	Review	not applicable	not applicable	not applicable	n/a	n/a	not specified	yes	yes	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
39	Peng et al.	2013	Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems	Review	not applicable	not applicable	not applicable	n/a	n/a	not specified	yes	yes	no	yes	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
40	Wu et al.	2017	Review on Life Cycle Assessment of Energy Payback of Solar Photovoltaic Systems and a Case Study	Conference paper	not applicable	not applicable	not applicable	n/a	n/a	not specified	no	yes	no	yes	yes	yes	yes	no	no	no
41	Rabaia et al.	2021	Environmental impacts of solar energy systems: A review	Journal article	not applicable	not applicable	not applicable	n/a	n/a	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
42	Gerbinet et al.	2014	Life Cycle Analysis (LCA) of photovoltaic panels: A review	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
43	Rajput et al.	2018	Life cycle assessment of the 3.2 kW cadmium telluride (CdTe) photovoltaic system in composite climate of India	Journal article	not specified	not specified	not specified	n/a	n/a	not specified	yes	yes	no	no	yes	no	yes	yes	yes	no
44	Ansanelli et al.	2021	A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels	Journal article	24 ton of EoL c-Si PV panels	industry data; ecoinvent 3.5 (2018); literature	yes	primary and secondary data	2018	ReCiPe2016	no	no	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	yes
45	Herceg et al.	2020	Influence of waste management on the environmental footprint of electricity produced by photovoltaic systems	Journal article	1 kWh	literature	no	secondary data	n/a	ILCD 2011	no	yes	no	yes	yes	yes	yes	yes	yes	yes
46	Lunardi et al.	2019	Life cycle assessment of two experimental recycling processes for c-si solar modules	Conference paper	1 PV module	Ecoinven 3.2 (2015); experimental data from laboratories	yes	primary and secondary data	2015	ReCiPe method	no	no	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	yes
47	Eskew et al.	2018	An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand	Journal article	2190 MWh of electricity production for the next 30 years	industry data; literature; ecoinvent	yes	primary and secondary data	2013	ReCiPe version 1.13	yes	yes	no	no	yes	yes	yes	yes	yes	yes
48	Ritzen et al.	2019	Carrying capacity based environmental impact assessment of Building Integrated Photovoltaics	Journal article	1 m2	ecoinvent; literature	yes	secondary data	n/a	not specified	no	no	no	yes	yes	not specified	not specified	yes	not specified	yes
49	Maani et al.	2020	Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels	Journal article	1 m2	Ecoinvent; data from laboratories	yes	primary and secondary data	2016	TRACI	no	no	no	no	no	no	no	no	no	yes
50	Clemons et al.	2021	Life cycle assessment of a floating photovoltaic system and feasibility for application in Thailand	Journal article	5250 GWh of electricity generated over lifetime	ecoinvent; literature; industry data	yes	primary and secondary data	n/a	Recipe	no	no	no	no	yes	yes	yes	yes	yes	yes

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
31	no	not applicable	yes	yes	irradiation; lifetime	China; EU	not specified	not specified	Nigeria	1	mono-si	Ground mounted	not applicable	Yes	14.9% mono module	1450 - 2200 kWh/m2*year	20; 25; 30	not specified
32	no	not applicable	yes	no	not applicabel	EU; China; USA	not applicable	not applicable	Nigeria	1	mono-si	Ground mounted	not applicable	No	15.4% mono module	1493 - 2223 kWh/m2*year	20; 30	notapplicable
33	not applicable	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2	mono-si; multi-si; a-SI; CdTE; CIS	both	not applicable	no	not applicable	not applicable	not applicable	not applicable
34	yes	simapro	no	yes	irradiation	China	China	same	Spain	1	multi-si	rooftop	not applicable	no	not specified	1400 - 1900 kWh/m2*year	not specified	not specified
35	not applicable	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2; 3	mono-si; multi-si; a-SI; cdte; CIS; perovskite; QDSSC	both	not applicable	no	mono 8.5-20.1; multi 10-18; aSi 5.5-12.4; cdte 8-12.4; CIS 10-11.5; DSSC 7-12; PSC 2-15.4; QDSSC 10-14 modules	570 - 2200 kWh/m2*year	20; 25; 30	not specified
36	not applicable	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2; 3	mono-si; multi-si; a-SI; cdte; CIS; CIGS; perovskite; OPV; DSSC; QD	both	not applicable	no	mono 16-22; multi 15-18; asi 4-8; cdte 10-15; CIS 10-13; CIGS 20;PSC 19-22; OPV 4-5 not specified if cell or module	not applicable	not applicable	not applicable
37	not applicable	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	2; 3	Cdte; a-SI; CIS; CIGS; OPV; perovskite	Not specified	not applicable	no	not specified	not applicable	not applicable	not applicable
38	not applicable	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2	mono-si; multi-si; a-SI	both	not applicable	no	asi 5.7-10; mono 7.3-14; multi 10-15.8 not specified if cell or module	not applicable	20; 25; 30	not specified
39	not applicable	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2	mono-si; multi-si; a-SI; cdte; CIS	both	BIPV	no	mono 12-14; multi 10.7-14; aSi 5-7; cdte 6-10.9; CIS 10.5-11 module	573 - 2000 kWh/m2*year	not applicable	not applicable
40	no	not applicable	yes	no	not applicabel	China	China	same	China	1	multi-si	ground mounted	not applicable	no	17.5% multi not specified if cell or module	2017 kWh/m2*year	30	not specified
41	not specified	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2; 3	mono-si; multi-si; a-SI; Cdte; CIS; CIGS; GaaS; Perovskite; DSSC; QD	both	not applicable	no	mono 16-22; multi 15-18; asi 8; cdte 10-15; CIS 10-13; CIGS 20; PSC 19-22; DSSC 10; QD 1.9 cells	not applicable	not applicable	not applicable
42	not specified	not applicable	not applicable	not applicable	not applicabel	not applicable	not applicable	not applicable	not applicable	1; 2	mono-si; multi-si; a-Si	both	BIPV	no	silicon PV 6.3-15% modules	not applicable	not applicable	not applicable
43	no	not applicable	yes	no	not applicabel	not specified	not specified	not specified	India	2	cdte	rooftop	not applicable	no	11% cdte module	not specified	25	not specified
44	yes	simapro v9	no	no	not applicabel	not applicable	not applicable	not applicable	not applicable	1	mono-si; multi-si	not applicable	not applicable	no	not specified	not applicable	not specified	not specified
45	not specified	not specified	not specified	no	not applicabel	average market share data	not specified	not specified	Germany	1	mono-si; multi-si	rooftop	not applicable	no	14 mono; 13.6 multi module	1.055 kWh/m2	30	15 inverters; 30 mounting structure; 30 cabling
46	not specified	not specified	not specified	no	not applicabel	not applicable	not applicable	not applicable	not applicable	1	not specified	not applicable	not applicable	no	not specified	not applicable	not applicable	not applicable
47	yes	simapro	no	no	not applicabel	Thailand	Mounting Australia; electrical components India	different	Thailand	1	multi-si	rooftop	not applicable	no	16.2 multi modules	not specified	30	15 inverter
48	not specified	not specified	not specified	no	not applicabel	not specified	not specified	not specified	Netherlands	1; 2	multi-si; a-Si; CIGS	rooftop	BIPV	no	not specified	not specified	30	not specified
49	yes	gabi 8.1	no	no	not applicabel	not specified	not applicable	not applicable	not specified	1; 2	c-SI; cdte	not applicable	not applicable	no	not specified	not applicable	25	not applicable
50	not specified	not specified	not specified	no	not applicabel	China	not specified	not specified	Thailand	1	multi-si	not applicable	floating	no	13 multi modules	1670 to 1895 kWh/m2	30	not specified

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
51	Dias et al.	2021	Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination – technical, environmental and economic analyses	Journal article	5 W modules	ecoinvent	no	secondary data	n/a	recipe	no	no	no	no	no	no	no	no	no	yes
52	Li et al.	2021	Life cycle assessment of semi-transparent photovoltaic window applied on building	Journal article	not specified	Ecoinvent; literature; industry data	yes	primary and secondary data	n/a	ISCP 2010, CML 2002, IMPACT2002	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
53	Kittner et al.	2013	An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand	Journal article	2400 MWh of electricity generated	literature	no	secondary data	n/a	not specified	yes	yes	no	no	yes	yes	yes	yes	yes	no
54	Mohr et al.	2013	Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate	Journal article	1 kWh	industry data; literature; ecoinvent	yes	primary and secondary data	n/a	recipe	no	no	no	yes	yes	yes	yes	yes	yes	yes
55	Mustafa et al.	2019	Environmental performance of window-integrated systems using dye-sensitised solar module technology in Malaysia	Journal article	1 kWh	ecoinvent 3.3; literature; data from laboratory	yes	primary and secondary data	2016	Recipe Midpoint	yes	yes	no	yes	yes	yes	yes	yes	yes	no
56	Lim et al.	2022	Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules	Journal article	1000 panels	GaBi 9.0 professional database	no	secondary data	n/a	CML 2000	no	no	no	no	no	no	no	no	no	yes
57	Latunussa et al.	2016	Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels	Journal article	1 ton of modules	industry data; ecoinvent 3	yes	primary data	2013	midpoint impact categories recommended from ILCD handbook	no	no	no	yes	no	no	no	no	no	yes
58	Bravi et al.	2011	Life cycle assessment of a micromorph photovoltaic system	Journal article	not specified	industry data; ecoinvent 2.2	yes	primary and secondary data	2010	eco indicator 99	yes	yes	no	yes	yes	not specified	yes	not specified	yes	yes
59	Tripathy et al.	2016	A critical review on building integrated photovoltaic products and their applications	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	yes	yes	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
60	Anctil et al.	2020	Net energy and cost benefit of transparent organic solar cells in building-integrated applications	Journal article	The functional unit was the operation of one building for 20 years.	literature; direct measurement from laboratory	yes	primary and secondary data	n/a	traci 2.1 method	no	yes	no	yes	yes	not specified	not specified	not specified	not specified	no
61	Tsang et al.	2016	Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies	Journal article	1 kWh	ecoinvent 2.2; literature	yes	secondary data	2010	recipe	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
62	Rocchetti and Beolchini	2015	Recovery of valuable materials from end-of-life thin-film photovoltaic panels: Environmental impact assessment of different management options	Journal article	1 m2	ecoinvent 2.2;	no	secondary data	2010	CML method	no	no	no	no	no	no	no	no	no	yes
63	Parisi et al.	2014	The evolution of the dye sensitized solar cells from Grätzel prototype to up-scaled solar applications: A life cycle assessment approach	Review	1 g of dye	ecoinvent 2.2; literature; data from laboratory	yes	primary and secondary data	2010	recipe	yes	yes	no	yes	yes	yes	yes	yes	yes	no
64	Ito et al.	2016	Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world	Journal article	not specified	ecoinvent; literature;	yes	secondary data	n/a	cumulative energy demand 1.08; Intergovernmental Panel on Climate Change 2007 global warming potential of 100 years	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
65	Sengül and Theis	2011	An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use	Journal article	not specified	ecoinvent; literature; industry data	yes	primary and secondary data	2007	IMPACT 2002 method	yes	yes	no	yes	yes	yes	yes	yes	yes	no
66	Bogacka and Landrat	2017	Environmental impact of PV cell waste scenario	Journal article	1 module	ecoinvent; literature	yes	secondary data	2013	recipe	no	no	no	no	yes	yes	yes	yes	no	yes
67	Martinopoulos	2020	Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis	Journal article	4 kW	ecoinvent	no	secondary data	n/a	Eco-Indicator '99	no	no	no	no	yes	yes	yes	yes	yes	yes
68	Jayathissa et al.	2016	Life cycle assessment of dynamic building integrated photovoltaics	Journal article	kWh	ecoinvent 3.1;	no	secondary data	2014	IPCC 2007 methodology	yes	no	no	no	yes	yes	yes	yes	yes	yes
69	Sierra et al.	2020	Life cycle analysis of a building integrated photovoltaic system operating in Bogotá, Colombia	Journal article	kWh	ecoinvent 3.1;	no	secondary data	2014	CML2001 methodology	yes	no	no	no	yes	yes	yes	yes	yes	yes
70	Ludin et al.	2021	Environmental impact and levelised cost of energy analysis of solar photovoltaic systems in selected asia pacific region: A cradle-to-grave approach	Journal article	not specified	ecoinvent; primary data from installation	yes	primary and secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	yes	yes	yes	yes

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
51	yes	openLCA	no	no	not applicabel	not specified	not applicable	not applicable	not specified	1	multi-si	not applicable	not applicable	no	not specified	not applicable	20; 25	not applicable
52	yes	efootprint	no	yes	location; direction	China	China	same	China	1	mono-si	not applicable	bipv	not specified	not specified	provided as a map	25	not applicable
53	not specified	not specified	not specified	no	not applicabel	China; Japan; Germany	not specified	not specified	Thailand	1; 2	mono-si; a-Si	not applicable	bipv	no	not specified	4.8 kWh/m2/day	30	not specified
54	yes	simapro 7.3.0	no	no	not applicabel	not specified	not specified	not specified	Netherlands	2	a-SI; nanocrystalline silicon	rooftop	bipv	no	8 asi cells	1000 kWh/m2	20	not specified
55	yes	simapro	no	yes	lifetime; module efficiency	Malaysia	not specified	not specified	Malaysia	3	not specified	not applicable	bipv	Yes	dssc 5% module	1402.82 kWh/m2/year	20	10 to 15 inverter
56	yes	gabi 9.0	no	yes	revenue; raw material; interest rate	not specified	not applicable	not applicable	not specified	1	mono-si	not applicable	not applicable	no	not specified	not specified	25 to 30	not applicable
57	yes	simapro 8.0	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	1	not specified	not applicable	not applicable	no	not specified	not applicable	25; 30	not applicable
58	yes	simapro 7.1	no	no	not applicable	EU	not specified	not specified	Italy	3	micromorph tandem junction	rooftop	not applicable	no	not specified	1700 kWh/m2/yr	20	not specified
59	not specified	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	1; 2	mono-si; multi-si; a-Si; cdte; CIS	not applicable	bipv	no	not specified	not applicable	not specified	not specified
60	yes	simapro	no	no	not applicable	USA	not specified	not specified	USA	3	OPV	not applicable	bipv	no	10% OPV modules	not specified	20	not specified
61	yes	openlca v1.4.2	no	no	not applicable	not specified	not specified	not specified	not specified	1; 2; 3	mono-si; a-SI, OPV	rooftop	not applicable	no	OPV 5 modules	not specified	25	not specified
62	yes	gabi 5.0	no	no	not applicable	not specified	not applicable	not applicable	not specified	2	CIGS; cdte	not applicable	not applicable	no	not specified	not applicable	not specified	notapplicable
63	yes	simapro 7.3.3	no	no	not applicable	EU	Europe	same	not applicable	2; 3	DSSC, CIS; a-Si; cdte	rooftop	not applicable	no	8 DSSC modules	1700 kWh/m2 year for the South Europe, 1117 kWh/m2 year for the Central Europe and 950 kWh/m2 year for the North Europe	20	not specified
64	not specified	not specified	not specified	no	not applicable	France	Electrical France; structural in installation country	combination	France; Morocco	1; 2	mono-si; multi-si; Cdte; CIS	ground mounted	not applicable	no	15.9 mono; 21.1 mono; 15 poly; 13.2 cdte; 13 CIS modules	1500 to 2100 kWH/m2*year	30	30 inverters with 10% replacement every 10 year
65	yes	simapro	no	no	not applicable	not specified	not specified	not specified	not specified	1; 2; 3	mono-si; multi-si; cdte; cis; ribbon; QDPV; DSPV	ground mounted	not applicable	no	14% quantum dot, not specified if cell or module	1700 kWk/m2 yr	CIS 20; DSPV 10	not specified
66	yes	simapro	no	no	not applicable	not specified	not applicable	not applicable	not applicable	not specified	not specified	Not specified	not applicable	no	16% not specified technology modules	not applicable	28	not specified
67	yes	simapro	no	no	not applicable	China	China	same	Eu	1	multi-si	rooftop	not applicable	no	17.3 multi module	not specified	25	not specified
68	yes	openLCA	no	no	not applicable	Germany; Switzerland; Spain	not specified	not specified	Germany; Switzerland; Spain	2	CIGS	not applicable	bipv	no	11% CIGS not specified if cell or module	855 kWh/m2/year	20	not specified
69	yes	Umberto NXT LCATM	no	no	not applicable	England	not specified	not specified	Colombia	1	mono-si	not applicable	bipv	no	not specified	not specified	30	not specified
70	yes	simapro	no	no	not applicable	not specified	not specified	not specified	malaysia; thailand; indonesia	1; 2	mono-si; multi-si,a-SI	both	not applicable	Yes	mono and multi 12.8; aSi 8 not specified if cell or module	1572 to 1888 kWh/m2*year	25	not specified

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
71	Tian et al.	2021	Life cycle assessment of recycling strategies for perovskite photovoltaic modules	Journal article	1 m2	ecoinvent; literature	yes	secondary data	n/a	recipe	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
72	Perez et al.	2012	Façade-integrated photovoltaics: A life cycle and performance assessment case study	Journal article	kWh	literature; ecoinvent; industry data	yes	primary and secondary data	n/a	Cumulative Energy Demand (CED) 1.05 metric; 2007 IPCC GWP 100a model	yes	yes	no	yes	yes	yes	yes	yes	yes	not specified
73	Singh et al.	2021	Life cycle analysis of disposed and recycled end-of-life photovoltaic panels in australia	Journal article	1 kWh	ecoinvent 3.6; literature	yes	secondary data	2019	recipe	yes	no	no	no	yes	yes	yes	yes	yes	yes
74	Ng and Mithratne	2014	Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics	Review	not applicable	ecoinvent 2.1; literature	yes	secondary data	2009	not specified	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
75	Wang et al.	2018	Grid-connected semitransparent building-integrated photovoltaic system: The comprehensive case study of the 120kWp plant in Kunming, China	Journal article	not specified	literature	no	secondary data	n/a	not specified	yes	yes	no	no	yes	no	yes	no	no	no
76	Murphy and McDonnell	2017	A feasibility assessment of photovoltaic power systems in Ireland; a case study for the Dublin region	Journal article	not specified	ecoinvent	no	secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	yes	yes	yes	yes
77	Giacchetta et al.	2013	Evaluation of the environmental benefits of new high value process for the management of the end of life of thin film photovoltaic modules	Journal article	PV panel	ecoinvent; industry data	yes	primary and secondary data	n/a	IMPACT 2002	no	no	no	no	no	no	no	no	no	yes
78	Gressler et al.	2022	Advanced materials for emerging photovoltaic systems – Environmental hotspots in the production and end-of-life phase of organic, dye-sensitized, perovskite, and quantum dots solar cells	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	no	no	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
79	Leccisi and Fthenakis	2020	Life-cycle environmental impacts of single-junction and tandem perovskite PVs: A critical review and future perspectives	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	yes	no	no	yes	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
80	Liu et al.	2015	Lifecycle climate impacts and economic performance of commercial-scale solar PV systems: A study of PV systems at Nevada's Desert Research Institute (DRI)	Journal article	not specified	SimaPro	no	secondary data	n/a	not specified	yes	yes	no	no	yes	yes	yes	yes	no	yes
81	Nicholls et al.	2015	Financial and environmental analysis of rooftop photovoltaic installations with battery storage in Australia	Journal article	not specified	not specified	not specified	n/a	n/a	not specified	no	yes	no	yes	yes	not specified	yes	yes	no	no
82	Leccisi and Fthenakis	2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV	Journal article	not specified	ecoinvent 3; literature	yes	secondary data	n/a	not specified	no	yes	no	yes	yes	no	yes	no	no	no
83	Dias et al.	2022	High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment	Journal article	1 tonne of silicon based waste modules	ecoinvent; literature	yes	secondary data	n/a	midpoint impact categories from the ILCD method	no	no	no	no	no	no	no	no	no	yes
84	Fouad et al.	2019	Life cycle assessment for photovoltaic integrated shading system with different end of life phases	Journal article	not specified	literature	no	secondary data	n/a	ILCD recommendation	no	no	no	no	yes	yes	no	yes	yes	yes
85	Pal and Kilby	2019	Using Life Cycle Assessment to Determine the Environmental Impacts Caused by Solar Photovoltaic Systems	Conference paper	kWh	literature	no	secondary data	n/a	IMPACT 2002+	no	no	no	no	yes	no	no	no	no	no
86	Yue et al.	2014	Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis	Journal article	1 m2	Chinese Life Cycle Database	no	secondary data	n/a	not specified	yes	yes	no	yes	yes	no	no	no	no	no
87	Soares et al.	2018	LCA study of photovoltaic systems based on different technologies	Journal article	not specified	ecoinvent 3.3;	no	secondary data	2016	Eco-indicator 99, Intergovernmental Panel on Climate Change (IPCC) 2013, International Reference Life Cycle Data System (ILCD) 2016, Cumulative Energy Demand 2015,	no	yes	no	no	yes	no	no	no	no	no
88	Lunardi et al.	2018	A comparative life cycle assessment of chalcogenide/Si tandem solar modules	Journal article	1 kWh	literature; communication with researchers	yes	primary and secondary data	n/a	not specified	yes	yes	no	no	yes	yes	no	yes	yes	yes
89	Garcıa-Valverde et al.	2010	Life cycle analysis of organic photovoltaic technologies	Journal article	The functional unit is 1 kg of the 99% HT-couple regioregular P3HT.	not specified	not specified	n/a	n/a	not specified	yes	yes	no	yes	yes	no	no	no	no	no
90	Vellini et al.	2017	Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels	Journal article	1 m2	ecoinvent 2.2;	no	secondary data	2010	CML 2001	no	yes	no	no	yes	not specified	not specified	yes	yes	yes

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/ combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/ agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
71	not specified	not specified	not specified	no	not applicable	not specified	not specified	not specified	EU	3	perovskite	rooftop	not applicable	no	11.68; 16.64; 16.96 perovskite module	1,700 kWhm−2	5	not specified
72	yes	simapro	no	no	not applicable	USA; EU	not specified	not specified	USA	1; 2	mono-si, multi-si, cdte	not applicable	bipv	no	not specified	1430kWh/m2/year, and on a south-facing latitude-tilt plane is 1615kWh/m2/year	30	15 inverter
73	yes	openlca	no	no	not applicable	not specified	not specified	not specified	Australia	1	not specified	rooftop	not applicable	no	not specified	not specified	30	not specified
74	not specified	not specified	not specified	no	not applicable	Japan; germany; taiwan	Inverter imported; structural consider Singapore electricity mix	different	Singapore	2	a-SI; microcrystalline silicon	not applicable	bipv	no	3.32 to 8 semi transparent modules	not specified	25	not specified
75	no	not applicable	yes	no	not applicable	not specified	not specified	not specified	China	1	mono-si	not applicable	bipv	not specified	8.25 mono cells	not specified	25	not specified
76	no	not applicable	yes	no	not applicable	not specified	not specified	not specified	Ireland	1	mono-si	rooftop	not applicable	no	16.5 mono modules	963 kWh/m2*year	30	15 inverter
77	yes	simapro 7.1	no	no	not applicable	not applicable	not applicable	not applicable	not applicable	2	cdte	not applicable	not applicable	no	not specified	not applicable	not specified	not applicable
78	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable	3	OPV; perovskite; DSSC; QDSC	both	not applicable	not specified	not specified	1700 kWh/m2	PSC 1-20; OPV 1.5-20; DSSC 20; QDSC 25	not applicable
79	not specified	not specified	not specified	no	not applicable	not applicable	not applicable	not applicable	not applicable	3	perovskite; tandem	not applicable	not applicable	no	6.5 to 27 perovskite not specified if cell or module	1700 kWh/m2*year	1 to 30	not applicable
80	yes	simapro	no	yes	efficiency of PV modules production; lifetime; efficiency of BOS production	not specified	not specified	not specified	USA	1	multi-si	both	not applicable	no	12.7 to 16.5 multi not specified if cell or module	not specified	25	not specified
81	no	not applicable	yes	yes	state emission intensity; battery lifetime	Australia	Australia	same	Australia	1	multi-si	rooftop	not applicable	Yes	15.62 multi cell	4.5 - 5.5 kWh/m2*day	25 modules;	10 inverters; 15 battery
82	yes	simapro9	no	yes	irradiation; lifetime; module efficiency	USA	not specified	not specified	not applicable	3	perovskite, multi-si, cigs, cdte	ground mounted	not applicable	no	19.3 perovskite module	1300 kWh/(m2*year), 1800 kWh/(m2*year), and 2300 kWh/(m2*year)	10; 20; 30	15 inverters
83	not specified	not specified	not specified	no	not applicable	not applicable	not applicable	not applicable	not applicable	1	not specified	Not specified	not applicable	no	not specified	not applicable	not specified	not applicable
84	yes	gabi	no	no	not applicable	not specified	not applicable	not applicable	not specified	1	multi-si	not applicable	bapv	no	14 multi module	not specified	25	not applicable
85	yes	simapro	no	no	not applicable	not specified	not applicable	not applicable	not specified	1	multi-si	Not specified	not applicable	no	not specified	not specified	not specified	not applicable
86	yes	ebalance v4.0	no	no	not applicable	China; EU	not applicable	not applicable	China; EU	1	mono-si; multi-si; ribbon silicon	not applicable	not applicable	no	14 mono; multi 13.2; aSi 12 modules	1700 kWh/m2*year	30	not applicable
87	yes	openlca 1.6.3	no	no	not applicable	not specified	not applicable	not applicable	Brazil	1; 2	mono-si; multi-si; ribbon; CIS; a-Si;	not applicable	not applicable	no	mono 23.5; multi 20.5; aSi 13; rribbon 18.5; CIS 20 modules	(4.25–6.5 kWh.m−2.day−1)	not specified	not applicable
88	yes	gabi	no	no	not applicable	China	not applicable	not applicable	not specified	3	tandem cells	Not specified	not applicable	no	22 tandem not specified if cell or module	1700 kWh/m2/year	20	not applicable
89	not specified	not specified	not specified	no	not applicable	EU	not applicable	not applicable	EU	3	OPV	Not specified	not applicable	no	5 organic modules	1700 kWh/m2/year of irradiance	15	not applicable
90	yes	gabi	no	yes	module efficiency; irradiation; primary energy in production and installation; grid efficiency	not specified	not specified	not specified	Italy	1; 2	Silicon; cdte	Not specified	not applicable	no	15.1 aSi; 13.4 cdte modules	not specified	30	not specified

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
91	Chen et al.	2016	Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: A case study in China	Journal article	1 kW	ecoinvent; literature	yes	secondary data	n/a	recipe	yes	yes	no	no	yes	no	no	no	no	no
92	Collier et al.	2014	Life cycle environmental impacts from CZTS (copper zinc tin sulfide) and Zn3P2 (zinc phosphide) thin film PV (photovoltaic) cells	Journal article	1 kWh	ecoinvent; literature; data from laboratory	yes	primary and secondary data	n/a	traci 2.1 method	yes	no	no	yes	yes	no	no	no	no	no
93	Huang et al.	2017	Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process	Journal article	1 kW	literature; industry data	yes	primary and secondary data	n/a	recipe	no	no	no	no	yes	no	no	no	no	yes
94	Muller et al.	2021	A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory	Journal article	1 kW module and 1 kWh electricity	ecoinvent 3.7; literature	yes	secondary data	2020	16 categoried EU PEFCR	yes	no	no	no	yes	yes	no	no	no	yes
95	Fu et al.	2015	Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China	Journal article	1 kWh	ecoinvent; literature;	yes	secondary data	n/a	CML 2001 impact assessment	yes	yes	no	yes	yes	no	no	no	no	no
96	Jia et al.	2020	Life-cycle assessment of p-type multi-Si back surface field (BSF) solar module in China of 2019	Journal article	1 kWh	Ecoinvent; industry data	yes	primary and secondary data	2007	recipe 2016	no	yes	no	yes	yes	yes	no	yes	yes	yes
97	Li et al.	2022	A comprehensive life cycle assessment study of innovative bifacial photovoltaic applied on building	Journal article	not specified	ecoinvent; industry data	yes	primary and secondary data	n/a	not specified	no	yes	yes	yes	yes	yes	not specified	yes	yes	yes
98	Held and Ilg	2011	Update of environmental indicators and energy payback time of CdTe PV systems in Europe	Review	1 m2	gabi 4 datasets; industry data	yes	primary and secondary data	n/a	CML 2001	yes	yes	no	yes	yes	no	yes	yes	yes	yes
99	Resalati et al.	2022	Life cycle assessment of different chalcogenide thin-film solar cells	Journal article	1 kWh	industry data; literature; Gabi database	yes	primary and secondary data	n/a	CML 2001	yes	no	no	no	yes	no	no	no	no	no
100	Pallas et al.	2020	Life cycle assessment of emerging technologies at the lab scale: The case of nanowire-based solar cells	Journal article	1 kWh	Ecoinvent; data from laboratories; literature	yes	primary and secondary data	2010	CML 2001	no	no	no	no	yes	not specified	no	yes	yes	no
101	Tsang et al.	2016	A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells	Journal article	1 W	data from lab; literature; patents; industry data; ecoinvent 2.2	yes	primary and secondary data	2010	RECIPE	no	yes	no	yes	yes	not specified	no	no	no	no
102	Celik et al.	2016	Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab	Journal article	1 kWh	literature; ecoinvent; data from laboratory	yes	primary and secondary data	n/a	TRACI; RECIPE;	yes	yes	no	yes	yes	not specified	no	not specified	not specified	no
103	Krebs-Moberg et al.	2021	Third generation of photovoltaic panels: A life cycle assessment	Journal article	3.6 GW	literature; ecoinvent	yes	secondary data	2013	recipe	no	no	no	no	yes	yes	no	yes	not specified	yes
104	Błaszczyk et al.	2021	Environmental performance of dye-sensitized solar cells based on natural dyes	Journal article	1 kWh	literature; ecoinvent 3.5; data from laboratory; field visit	yes	primary and secondary data	2018	IMPACT 2002	no	no	no	yes	yes	no	no	no	yes	no
105	Hengevoss et al.	2016	Life Cycle Assessment and eco-efficiency of prospective, flexible, tandem organic photovoltaic module	Journal article	m2 and kWh	ecoinvent 2.2; literature; industry data	yes	primary and secondary data	2010	EPBT; GWP;	yes	yes	no	yes	yes	not specified	yes	not specified	not specified	no
106	Correa Guerrero et al.	2021	Energy performance of perovskite solar cell fabrication in Argentina. A life cycle assessment approach	Journal article	1 m2	literature	no	secondary data	n/a	not specified	no	yes	no	yes	yes	not specified	not specified	not specified	not specified	not specified
107	Zhang et al.	2022	Techno-economic and environmental sustainability of industrial-scale productions of perovskite solar cells	Journal article	1 m2	GaBi professional database, ecoinvent database, literature	yes	secondary data	n/a	traci 2.1 method	no	no	no	no	yes	yes	not specified	yes	yes	yes
108	Jia et al.	2021	Life cycle assessment on PERC solar modules	Journal article	1 kWh	industry data; ecoinvent 3.5	yes	primary and secondary data	2018	IPCC 2013 GWP 100a V1.03; USEtox 2; recipe 2016; CML	yes	no	no	no	yes	yes	no	yes	yes	yes
109	Espinosa et al.	2015	Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective	Journal article	1 kWh	literature; ecoinvent	yes	secondary data	2014	ILCD	yes	yes	no	yes	yes	no	no	no	no	no
110	Wong et al.	2016	Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	yes	yes	no	yes	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/ combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/ agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
91	not specified	not specified	not specified	no	not applicable	China	not applicable	not applicable	China	1	mono-si	Not specified	not applicable	no	15.7 mono cells	2780 to 7560 MJ/m2*a	25	not applicable
92	yes	gabi	no	no	not applicable	USA	not applicable	not applicable	not specified	3	CZTS; ZnP3	Not specified	not applicable	no	CZTS 10% not specified if cell or module	1700 kWh/m2*year	30	not applicable
93	yes	gabi	no	no	not applicable	China	not applicable	not applicable	not applicable	1	multi-si	Not specified	not applicable	no	16 multi cells	not specified	25	not applicable
94	yes	simapro v9	no	yes	module materials	China; germany; EU	not applicable	not applicable	EU	1	mono-si	Not specified	not applicable	no	19.4; 19.79 mono-si modules	1391 kWh/m2*year	30	not applicable
95	yes	gabi4	no	yes	energy and material consumption in production process	China	not applicable	not applicable	not applicable	1	multi-si	not applicable	not applicable	no	16 multi cells	772 to 2100 kWh/m2*year	25	not applicable
96	yes	simapro 8.3	no	yes	module efficiencY; manufacturing process improvement;	China	not applicable	not applicable	China	1	multi-si	ground mounted	not applicable	no	18.8 multi-si cells	6368.77 MJ/m2*year	25; 30	not applicable
97	no	not applicable	yes	no	not applicable	China	not applicable	not applicable	China	1	mono-si	not applicable	bipv	no	not specified	1300 to 1800 kWh/m2*year	25	not specified
98	yes	gabi 4	no	yes	location	Germany	not specified	not specified	EU	2	cdte	ground mounted	not applicable	no	10.9 cdte modules	1700 kWh/m2/yr	30	not specified
99	yes	gabi 9.2	no	yes	module efficiency	EU	not applicable	not applicable	UK	2; 3	CIGS; CZTS; SB2Se3	Not specified	not applicable	no	11 CZTS; 7.6 SB2SE3 not specified if cell or module	850 kWh/m2*year	30	not applicable
100	yes	CMLCA	no	no	not applicable	not specified	not applicable	not applicable	EU	3	nanowire based solar cells	Not specified	not applicable	no	25% nanowire based modules	1700 kWh/m2*year	30	not applicable
101	yes	openlca v1.4	no	yes	manufacturing options	EU	not applicable	not applicable	not applicable	1; 2; 3	multi-si; a-SI; OPV	both	not applicable	no	5 OPV ; 13.2 multi; 6.5 aSi cells	1700 kWh/m2*year	25	not applicable
102	yes	gabi 6.0	no	yes	lifetime; module efficiency	USA	not applicable	not applicable	not specified	1; 2; 3	perovskite; mono-si; multi-si; CIS; cdte; aSi	Not specified	not applicable	no	6.4 to 15 perovskite cells	1700 kWh/m2*year	5	not applicable
103	yes	simapro	no	no	not applicable	Thailand	not applicable	not applicable	Thailand	1; 3	multi-si; OPV; Perovskite	Not specified	not applicable	no	multi 19.9; OPV 8,7; perovskite 11.6 modules	not specified	30	not applicable
104	not specified	not specified	not specified	yes	module efficiency	Poland	not applicable	not applicable	Poland	3	DSSC	Not specified	not applicable	no	1; 2; 5 DSSC cells	1000 kWh/m2*year	1	not applicable
105	yes	emis v5.7	no	no	not applicable	EU	Europe	same	EU	1; 2; 3	OPV; multi-si; cdte	rooftop	not applicable	no	8-10 % OPV not specified if cell or module	1000-2000 kWh/m2*year	15; 20	not specified
106	not specified	not specified	not specified	yes	module efficiency	Argentina	not specified	not specified	Argentina	3	perovskite	Not specified	not applicable	no	15 perovskite modules	1.53 MW/m2year	0.25 to 30	not specified
107	yes	gabi	no	yes	module efficiency	not specified	not applicable	not applicable	not specified	1; 3	perovskite; multi-si	Not specified	not applicable	no	not specified	1860 kWh/m2/year	30	not specified
108	yes	simapro	no	no	not applicable	China	not applicable	not applicable	China	1	PERC	ground mounted	not applicable	no	20; 21% PERC modules	1573 kWh/m2*year	30	not applicable
109	yes	simapro	no	yes	lifetime	not specified	not applicable	not applicable	EU	3	perovskite	Not specified	not applicable	no	11.5; 15.4 perovskite cells	not specified	1 to 15	not applicable
110	not applicable	not applicable	not applicable	yes	irradiation	not applicable	not applicable	not applicable	not applicable	1	mono-si; multi-si	both	not applicable	not specified	8.5-20 mono; 10-16 multi modules	not applicable	not applicable	not applicable

Introductory information					Methodological aspects															
Number	Author	Year	Title	Type of contribution	Functional unit	Life cycle inventory				Life cycle impact assessment					Boundaries and phases					
					FU used	Data source	Multiple data source category	Primary/secondary data	ecoinvent version	LCIA method	GWP	EPBT	Co2PBT	CED	Module manufacturing	Transportation	BOS manufacturing	Installation	Use	EoL
111	Carneiro et al.	2022	Energy consumption and carbon footprint of perovskite solar cells	Journal article	1 module	ecoinvent; literature; data from construction	yes	primary and secondary data	2018	ILCD 2018 MidPoint	no	no	no	no	yes	no	no	no	no	no
112	Sarialtin et al.	2021	Environmental assessment of transparent conductive oxide-free efficient flexible organo-lead halide perovskite solar cell	Journal article	1 m2 and 1 kWh	literature; ecoinvent	yes	secondary data	n/a	ILCD	no	yes	no	yes	yes	no	no	no	no	no
113	Ahangharnejhad et al.	2020	Environmental Impact per Energy Yield for Bifacial Perovskite Solar Cells Outperforms Crystalline Silicon Solar Cells	Journal article	1 m2 and 1 kWh	Ecoinvent; literature; data from laboratory	yes	primary and secondary data	n/a	not specified	yes	yes	no	yes	yes	no	no	no	no	no
114	Zahedi et al.	2022	Environmental and damage assessment of transparent solar cells compared with first and second generations using the LCA approach	Journal article	1 kWh	not specified	not specified	n/a	n/a	recipe	no	no	no	no	yes	yes	no	no	no	no
115	Reich et al.	2011	Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options	Review	not applicable	ecoinvent	no	secondary data	n/a	not specified	yes	no	no	no	yes	yes	no	not specified	no	yes
116	Lizin et al.	2013	Life cycle analyses of organic photovoltaics: A review	Review	not applicable	not applicable	not applicable	n/a	n/a	not applicable	no	yes	no	yes	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
117	Salameh et al.	2020	Life cycle analysis comparison between single crystalline solar cells and poly crystaline gallium in UAE	Conference paper	not specified	not specified	not specified	n/a	n/a	not specified	no	no	no	yes	yes	yes	no	not specified	yes	yes
118	Kim and Fthenakis	2011	Comparative life-cycle energy payback analysis of multi-junction a-SiGe and nanocrystalline/a-Si modules	Journal article	not specified	Ecoinvent; literature; industry data	yes	primary and secondary data	n/a	not specified	no	yes	no	yes	yes	yes	no	yes	yes	no
119	Hong et al.	2016	Life cycle assessment of multicrystalline silicon photovoltaic cell production in China	Journal article	1 kWh	literature; industry data; ecoinvent	yes	primary and secondary data	2010	IMPACT 2002	no	no	no	no	yes	no	no	no	no	no
120	Yang et al.	2015	Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade	Journal article	1 kW	literature; industry data; ecoinvent 2.1	yes	primary and secondary data	2009	CML 2001	no	no	no	no	yes	yes	no	no	no	no
121	Agostini et al.	2021	Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment	Journal article	1 MJ	industry data; ecoinvent	yes	primary and secondary data	2016	EF Life Cycle Impact Assessment method;	yes	no	no	yes	not specified	not specified	not specified	not specified	not specified	not specified
122	Serrano-Lujan et al.	2017	The greenest decision on photovoltaic system allocation	Journal article	1 kW	literature; industry data	yes	primary and secondary data	n/a	not specified	yes	yes	no	yes	yes	yes	no	yes	yes	no
123	De Lima et al.	2021	The role of national energy policies and life cycle emissions of pv systems in reducing global net emissions of greenhouse gases	Journal article	not specified	literature	no	secondary data	n/a	not specified	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
124	Zarzavilla et al.	2022	Comparison of Environmental Impact Assessment Methods in the Assembly and Operation of Photovoltaic Power Plants: A Systematic Review in the Castilla—La Mancha Region	Journal article	not specified	not specified	not specified	n/a	n/a	not specified	no	no	yes	yes	yes	yes	not specified	not specified	yes	yes
125	Choi et al.	2021	Combined land use of solar infrastructure and agriculture for socioeconomic and environmental co-benefits in the tropics	Journal article	not specified	literature; data from field visits	yes	primary and secondary data	n/a	not specified	no	no	no	yes	yes	yes	yes	yes	yes	yes
126	Pascaris et al.	2021	Life cycle assessment of pasture-based agrivoltaic systems: Emissions and energy use of integrated rabbit production	Journal article	MWh electricity and kg meat	literature, ecoinvent	yes	secondary data	2013	IPCC 2013 Global Warming Potential (GWP) 100a V1.03 and cumulative energy demand (CED) V1.11	no	no	no	no	yes	not specified	yes	not specified	yes	no
127	Leon and Isihara	2018	Assessment of new functional units for agrivoltaic systems	Journal article	m2	ecoinvent; literature	yes	secondary data	n/a	not specified	no	no	no	no	yes	not specified	yes	not specified	yes	no
128	Leon and Isihara	2018	Influence of allocation methods on the LC-CO2 emission of an agrivoltaic system	Journal article	1 kg crop production; 1 ha land	literature; ecoinvent	yes	secondary data	n/a	not specified	no	no	no	no	yes	not specified	yes	not specified	yes	no
129	Mukisa et al.	2021	Multi criteria analysis ranking of solar photovoltaic modules manufacturing countries by an importing country: A case of Uganda	Journal article	50 kW	literature	no	secondary data	n/a	not specified	yes	yes	yes	no	yes	yes	no	no	no	no

Number	Methodological aspects					PV system hypothesis									PV technical parameters			
	Software			Sensitivity analysis		Modules manufacturing location	BOS manufacturing location		Installation location	Modules generation and technology		Installation configuration	Emerging PV applications	Storage system	Module efficiency	Irradiation	Lifetime	
	Software	Software name	tailored model	Sensitivity analysis inclusion	Sensitivity parameter	country of modules manufacturing	country of BOS manufacturing	BOS country vs Modules country (same/different/combination)	Country installation	PV generation	Module technology	Ground Mounted / Rooftop	BIPV/BAPV/Floating/agrivoltaic	Inclusion of Storage system	Module efficiency (%)	Value of irradiation	Modules lifetime	BOS lifetime
111	yes	simapro	no	no	not applicable	Portugal	not applicable	not applicable	not specified	3	perovskite	Not specified	not applicable	no	8.7 perovskite modules	not specified	not specified	not applicable
112	yes	gabi	no	yes	lifetime	not specified	not applicable	not applicable	not specified	3	perovskite	Not specified	not applicable	no	14% perovskite modules	1700 kWh/m2*year	5	not applicable
113	yes	gabi 8.0	no	no	not applicable	USA	not applicable	not applicable	USA	1; 3	perovskite; crystalline silicon	ground mounted	not applicable	no	not specified	4-5.5 kWh/m2*day	25	not applicable
114	yes	simapro	no	no	not applicable	China	not applicable	not applicable	Canada	1; 2; 3	multi-si; cdte; perovskite	Not specified	not applicable	no	poly 16; cdte 11; perovskite 7 modules	not specified	not specified	not applicable
115	yes	simapro	no	no	not applicable	EU	not applicable	not applicable	not specified	1	not specified	Not specified	not applicable	no	15 not specified technology modules	700 - 2500 kWh/m2*year	25	not applicable
116	not applicable	not applicable	not applicable	no	not applicable	not applicable	not applicable	not applicable	not applicable	3	OPV	Not specified	not applicable	no	2 OPV cells	not applicable	not applicable	not applicable
117	yes	CES edu pack software	no	no	not applicable	China	not applicable	not applicable	UAE	1	mono-si; multi-si	Not specified	not applicable	no	not specified	not specified	not specified	not applicable
118	not specified	not specified	not specified	no	not applicable	USA	not applicable	not applicable	USA	2	a-Si	rooftop	not applicable	no	8 a-Si modules	1200 to 2480 kWh/m2*year	10	not applicable
119	not specified	not specified	not specified	yes	manufacturing electricity and material consumption	China	not applicable	not applicable	China	1	multi-si	Not specified	not applicable	not specified	12.7 multi-si cells	not specified	not specified	not applicable
120	yes	simapro 7.3	no	yes	electricity and steam consumption; market share of imported multi crystalline silicon; coal burning share of electricity mix in china	China	not applicable	not applicable	not applicable	1	multi-si	not applicable	not applicable	no	not specified	not specified	not specified	not applicable
121	yes	gabi	no	no	not applicable	China	Mounting from China	combination	Italy	not specified	not specified	not applicable	agrivoltaic	no	19 not specified technology modules	not specified	25	12-13 inverter
122	no	not applicable	yes	yes	irradiation	141 countries combination are considered in this paper	not applicable	not applicable	141 countries combination are considered in this paper	1; 2; 3	cristalline silicon; cdte; OPV	Not specified	not applicable	no	cSi 18%; 14% cdte modules	1000-2500 kWh/m2*year	25	not applicable
123	no	not applicable	yes	yes	country grid carbon intensity	China	China	same	Brazil	not specified	not specified	Not specified	not applicable	no	not specified	1500 to 2100 kWH/m2*year	25	not specified
124	no	not applicable	yes	no	not applicable	not specified	not specified	not specified	Spain	1	mono-si; multi-si	ground mounted	not applicable	no	not specified	not specified	25	not specified
125	no	not applicable	yes	yes	energy requirement of patchouili cultivation	not specified	not specified	not specified	Indonesia	1	multi-si	Not specified	agrivoltaic	yes	not specified	not specified	30	not specified
126	yes	simapro	no	yes	External feeds for rabbits	not specified	not specified	not specified	USA	1	multi-si	ground mounted	agrivoltaic	no	not specified	not specified	30	not specified
127	yes	MILCA v2	no	yes	embodied CO2 in OPV; lifetime	not specified	not specified	not specified	Japan	3	OPV	ground mounted	agrivoltaic	no	2.7% opv modules	3.42 kWh/m2*day	10	10 inverter
128	yes	MILCA	no	yes	embodied CO2 in OPV; lifetime	not specified	not specified	not specified	Japan	3	OPV	ground mounted	agrivoltaic	no	2.7% opv not specified if cell or module	3.42 kWh/m2*day	10	10 inverter
129	no	not applicable	yes	yes	country energy efficiency; Transportation energy consumption; manufacturing energy consumtpion	USA, germany, china, brazil, india, australia	not applicable	not applicable	Uganda	1	silicon	not applicable	not applicable	no	15.29% silicon module	5–6 kWh/m2*day	not specified	not applicable

Appendix A.2: Impact of the life cycle phases

Number	Author	Year	Title	Modules manufacturing	BOS manufacturing	Transportation	Installation	Use	End-of-Life	End-of-Life benefits
1	Rashedi et Khanam	2020	Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method	not specified	not specified	no	not specified	not specified	not specified	not specified
2	Hou et al.	2016	Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China	70,5% CED; 71.92% CO2	13.42% CED; 14.19% CO2	0.7% - 1.91% of GHG	13% CED; 14% CO2	0.08% CED; 0.17% GHG	9,66% CO2	not specified
3	Yu et al.	2017	Life cycle assessment of grid-connected power generation from metallurgical route multi-crystalline silicon photovoltaic system in China	not specified	not specified	not specified	not specified	not specified	not specified	not specified
4	Kim et al.	2014	Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems	45% CED	52.20% CO2; 54.62% CED	not specified	not specified	not specified	not specified	not specified
5	Rahman et al.	2019	A life cycle assessment model for quantification of environmental footprints of a 3.6 kWp photovoltaic system in Bangladesh	31.90% CED	61.79% CED	0.58% of CED; 0.84% GHG	not specified	not specified	not specified	not specified
6	Fthenakis and Kim	2011	Photovoltaics: Life-cycle analyses	58% CED; 54% CO2	not specified	3.2% energy; 3.50 % GHG	0.1% CED; 0.2% CO2	1.1% CED; 0.9% CO2	1.7% CED; 1.9% CO2	not specified
7	Santoli et al.	2010	Life cycle assessment of electricity generated by photovoltaic systems manufactured in Europe and installed in buildings in the city of Rome	not specified	not specified	not specified	not specified	not specified	not specified	not specified
8	Szilágyi and Gróf	2020	Estimating the environmental footprint of a grid-connected 20 MWp photovoltaic system	not specified	not specified	not specified	0.4% CED	not specified	not specified	not specified
9	Nordin et al.	2020	Life-cycle assessment of residential-scale grid-connected photovoltaic system in malaysia based on monocrystalline silicon modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
10	Beylot et al.	2014	Environmental impacts of large-scale grid-connected ground-mounted PV installations	not specified	not specified	not specified	not specified	not specified	not specified	*-11% CO2; -9.49% CED
11	Raugei et al.	2020	What Are the Energy and Environmental Impacts of Adding Battery Storage to Photovoltaics? A Generalized Life Cycle Assessment	not specified	not specified	not specified	not specified	not specified	not specified	not specified
12	Liu et al.	2020	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	not specified	not specified	not specified	not specified	not specified	not specified	not specified
13	Luo et al.	2018	A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies	not specified	8.6% CED; 14% CO2	not specified	not specified	not specified	not specified	not specified
14	Piasecka et al.	2020	Eco-energetical life cycle assessment of materials and components of photovoltaic power plant	not specified	not specified	not specified	not specified	not specified	not specified	not specified
15	Desideri et al.	2012	Life Cycle Assessment of a ground-mounted 1778kWp photovoltaic plant and comparison with traditional energy production systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
16	Kim et al.	2014	Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea	78% CO2	not specified	not specified	not specified	not specified	not specified	not specified
17	Koulompis et al.	2020	Should photovoltaics stay at home? Comparative life cycle environmental assessment on roof-mounted and ground-mounted photovoltaics	not specified	not specified	not specified	not specified	not specified	not specified	not specified
18	Antonanzas et al.	2019	Comparative life cycle assessment of fixed and single axis tracking systems for photovoltaics	not specified	not specified	not specified	not specified	not specified	not specified	*-3.03% CO2
19	Üçtuğ and Azapagic	2018	Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries	not specified	not specified	not specified	not specified	not specified	not specified	not specified
20	de Wild-Scholten	2013	Energy payback time and carbon footprint of commercial photovoltaic systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
21	Santoyo-Castelazo et al.	2021	Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: A case study for Mexico	67% CO2	not specified	0.5% GWP	3.4% GWP	0.01% CO2	0.8% CO2	not specified
22	Pamponet et al.	2021	Energy balance and carbon footprint of very large-scale photovoltaic power plant	not specified	not specified	not specified	not specified	not specified	not specified	not specified
23	Leccisi et al.	2016	The energy and environmental performance of ground-mounted photovoltaic systems - A timely update	not specified	not specified	not specified	not specified	not specified	not specified	not specified

Number	Author	Year	Title	Modules manufacturing	BOS manufacturing	Transportation	Installation	Use	End-of-Life	End-of-Life benefits
24	Laleman et al,	2011	Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation	not specified	not specified	not specified	not specified	not specified	not specified	not specified
25	Mehedi et al.	2022	Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
26	Bayod-Rújula et al.	2011	Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems	63% CED; 59.2% CO2	not specified	not specified	not specified	not specified	not specified	not specified
27	Ito et al.	2011	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant	not specified	not specified	not specified	not specified	not specified	not specified	not specified
28	Stylos and Koroneos	2014	Carbon footprint of polycrystalline photovoltaic systems	not specified	48% CED;	not specified	not specified	not specified	not specified	not specified
29	Nordin et al.	2022	Energy and environmental impacts of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: A life-cycle approach	62.36% CED	20% CED; 16.52% GWP	0.48% CED	not specified	10.78% CED; 11.37% CO2	0.02% CED; 0.01% GW	not specified
30	Fthenakis and Leccisi	2021	Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends	not specified	not specified	not specified	not specified	not specified	not specified	not specified
31	Akinyele	2017	Environmental performance evaluation of a grid-independent solar photovoltaic power generation (SPPG) plant	not specified	not specified	not specified	not specified	not specified	not specified	not specified
32	Akinyele et al.	2017	Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria	not specified	not specified	not specified	not specified	not specified	not specified	not specified
33	Baharwanj et al.	2014	Life cycle inventory and assessment of different solar photovoltaic systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
34	Sumper et al.	2011	Life-cycle assessment of a photovoltaic system in Catalonia (Spain)	91% CO2	2.56% CED	11% CED; 0.66% CO2	2% CED; 3% CO2	not specified	not specified	not specified
35	Ludin et al.	2018	Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review	not specified	not specified	not specified	not specified	not specified	not specified	not specified
36	Muteri et al.	2020	Review on life cycle assessment of solar photovoltaic panels	not specified	not specified	not specified	not specified	not specified	not specified	not specified
37	Chatzisideris et al.	2016	Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies	not specified	not specified	not specified	not specified	not specified	not specified	not specified
38	Shewani et al.	2010	Life cycle assessment of solar PV based electricity generation systems: A review	not specified	not specified	not specified	not specified	not specified	not specified	not specified
39	Peng et al.	2013	Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
40	Wu et al.	2017	Review on Life Cycle Assessment of Energy Payback of Solar Photovoltaic Systems and a Case Study	84% CED	not specified	0.47% CED	not specified	not specified	not specified	not specified
41	Rabaia et al.	2021	Environmental impacts of solar energy systems: A review	not specified	not specified	not specified	not specified	not specified	not specified	not specified
42	Gerbinet et al.	2014	Life Cycle Analysis (LCA) of photovoltaic panels: A review	not specified	not specified	not specified	not specified	not specified	not specified	not specified
43	Rajput et al.	2018	Life cycle assessment of the 3.2 kW cadmium telluride (CdTe) photovoltaic system in composite climate of India	73% CED	not specified	not specified	not specified	9% CED	not specified	not specified
44	Ansanelli et al.	2021	A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels	not specified	not specified	not specified	not specified	not specified	not specified	not specified
45	Herceg et al.	2020	Influence of waste management on the environmental footprint of electricity produced by photovoltaic systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
46	Lunardi et al.	2019	Life cycle assessment of two experimental recycling processes for c-si solar modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
47	Eskew et al.	2018	An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand	not specified	not specified	not specified	not specified	not specified	not specified	*-30.83% GWP
48	Ritzen et al.	2019	Carrying capacity based environmental impact assessment of Building Integrated Photovoltaics	not specified	not specified	not specified	not specified	not specified	not specified	not specified
49	Maani et al.	2020	Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels	not specified	not specified	not specified	not specified	not specified	not specified	not specified
50	Clemons et al.	2021	Life cycle assessment of a floating photovoltaic system and feasibility for application in Thailand	67% CO2	not specified	not specified	not specified	not specified	0.1% CO2	not specified
51	Dias et al.	2021	Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination – technical, environmental and economic analyses	not specified	not specified	not specified	not specified	not specified	not specified	not specified

Number	Author	Year	Title	Modules manufacturing	BOS manufacturing	Transportation	Installation	Use	End-of-Life	End-of-Life benefits
52	Li et al.	2021	Life cycle assessment of semi-transparent photovoltaic window applied on building	23.49% CED; 20.99% CO2	not specified	4% CED; 3% GWP	27.06% CED; 28.36% CO2	not specified	5% CED; 5% CO2	not specified
53	Kittner et al.	2013	An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand	not specified	not specified	not specified	not specified	not specified	not specified	not specified
54	Mohr et al.	2013	Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate	not specified	16% CED;	not specified	not specified	not specified	not specified	not specified
55	Mustafa et al.	2019	Environmental performance of window-integrated systems using dye-sensitised solar module technology in Malaysia	not specified	8% CED; 7.40% CO2	2% CED; 1.8% CO2	not specified	7% CO2; 8% energy	not specified	not specified
56	Lim et al.	2022	Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
57	Latunussa et al.	2016	Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels	not specified	not specified	not specified	not specified	not specified	not specified	*-11.87% CED, -17.02% CO2
58	Bravi et al.	2011	Life cycle assessment of a micromorph photovoltaic system	not specified	not specified	not specified	not specified	not specified	not specified	not specified
59	Tripathy et al.	2016	A critical review on building integrated photovoltaic products and their applications	not specified	not specified	not specified	not specified	not specified	not specified	not specified
60	Anctil et al.	2020	Net energy and cost benefit of transparent organic solar cells in building-integrated applications	not specified	not specified	not specified	not specified	not specified	not specified	not specified
61	Tsang et al.	2016	Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies	not specified	not specified	not specified	not specified	not specified	not specified	not specified
62	Rocchetti and Beolchini	2015	Recovery of valuable materials from end-of-life thin-film photovoltaic panels: Environmental impact assessment of different management options	not specified	not specified	not specified	not specified	not specified	not specified	not specified
63	Parisi et al.	2014	The evolution of the dye sensitized solar cells from Grätzel prototype to up-scaled solar applications: A life cycle assessment approach	not specified	not specified	not specified	not specified	not specified	not specified	not specified
64	Ito et al.	2016	Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world	not specified	not specified	not specified	not specified	not specified	not specified	not specified
65	Sengül and Theis	2011	An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use	not specified	21% CED;	not specified	not specified	not specified	not specified	not specified
66	Bogacka and Landrat	2017	Environmental impact of PV cell waste scenario	not specified	not specified	not specified	not specified	not specified	not specified	not specified
67	Martinopoulos	2020	Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis	not specified	not specified	not specified	not specified	not specified	not specified	not specified
68	Jayathissa et al.	2016	Life cycle assessment of dynamic building integrated photovoltaics	not specified	not specified	not specified	not specified	not specified	2.5% CO2	not specified
69	Sierra et al.	2020	Life cycle analysis of a building integrated photovoltaic system operating in Bogotá, Colombia	not specified	not specified	not specified	not specified	not specified	not specified	not specified
70	Ludin et al.	2021	Environmental impact and levelised cost of energy analysis of solar photovoltaic systems in selected asia pacific region: A cradle-to-grave approach	not specified	not specified	not specified	not specified	not specified	not specified	not specified
71	Tian et al.	2021	Life cycle assessment of recycling strategies for perovskite photovoltaic modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
72	Perez et al.	2012	Façade-integrated photovoltaics: A life cycle and performance assessment case study	not specified	not specified	not specified	not specified	not specified	not specified	not specified
73	Singh et al.	2021	Life cycle analysis of disposed and recycled end-of-life photovoltaic panels in australia	not specified	not specified	not specified	not specified	not specified	not specified	not specified
74	Ng and Mithraratne	2014	Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics	not specified	not specified	not specified	not specified	not specified	not specified	not specified
75	Wang et al.	2018	Grid-connected semitransparent building-integrated photovoltaic system: The comprehensive case study of the 120kWp plant in Kunming, China	not specified	not specified	not specified	not specified	not specified	not specified	not specified
76	Murphy and McDonnell	2017	A feasibility assessment of photovoltaic power systems in Ireland; a case study for the Dublin region	not specified	not specified	1.8% GWP	not specified	not specified	not specified	not specified
77	Giacchetta et al.	2013	Evaluation of the environmental benefits of new high value process for the management of the end of life of thin film photovoltaic modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
78	Gressler et al.	2022	Advanced materials for emerging photovoltaic systems – Environmental hotspots in the production and end-of-life phase of organic, dye-sensitized, perovskite, and quantum dots solar cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified

Number	Author	Year	Title	Modules manufacturing	BOS manufacturing	Transportation	Installation	Use	End-of-Life	End-of-Life benefits
79	Leccisi and Fthenakis	2020	Life-cycle environmental impacts of single-junction and tandem perovskite PVs: A critical review and future perspectives	not specified	not specified	not specified	not specified	not specified	not specified	not specified
80	Liu et al.	2015	Lifecycle climate impacts and economic performance of commercial-scale solar PV systems: A study of PV systems at Nevada's Desert Research Institute (DRI)	75% CED; 91% CO2	25% CED; 8% GHG	not specified	not specified	not specified	not specified	not specified
81	Nicholls et al.	2015	Financial and environmental analysis of rooftop photovoltaic installations with battery storage in Australia	83% CED	not specified	not specified	not specified	not specified	not specified	not specified
82	Leccisi and Fthenakis	2021	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV	not specified	not specified	not specified	not specified	not specified	not specified	not specified
83	Dias et al.	2022	High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment	not specified	not specified	not specified	not specified	not specified	not specified	not specified
84	Fouad et al.	2019	Life cycle assessment for photovoltaic integrated shading system with different end of life phases	not specified	not specified	not specified	not specified	not specified	not specified	not specified
85	Pal and Kilby	2019	Using Life Cycle Assessment to Determine the Environmental Impacts Caused by Solar Photovoltaic Systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
86	Yue et al.	2014	Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis	not specified	not specified	not specified	not specified	not specified	not specified	not specified
87	Soares et al.	2018	LCA study of photovoltaic systems based on different technologies	not specified	not specified	not specified	not specified	not specified	not specified	not specified
88	Lunardi et al.	2018	A comparative life cycle assessment of chalcogenide/Si tandem solar modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
89	Garcıa-Valverde et al.	2010	Life cycle analysis of organic photovoltaic technologies	not specified	not specified	not specified	not specified	not specified	not specified	not specified
90	Vellini et al.	2017	Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels	not specified	not specified	not specified	not specified	not specified	not specified	not specified
91	Chen et al.	2016	Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: A case study in China	not specified	not specified	not specified	not specified	not specified	not specified	not specified
92	Collier et al.	2014	Life cycle environmental impacts from CZTS (copper zinc tin sulfide) and Zn3P2 (zinc phosphide) thin film PV (photovoltaic) cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
93	Huang et al.	2017	Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process	not specified	not specified	not specified	not specified	not specified	not specified	not specified
94	Muller et al.	2021	A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory	95.31% CO2	not specified	1 to 3% impact CO2	not specified	not specified	1.6%; 2.5% CO2	not specified
95	Fu et al.	2015	Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China	not specified	not specified	<3% of CED	not specified	not specified	not specified	not specified
96	Jia et al.	2020	Life-cycle assessment of p-type multi-Si back surface field (BSF) solar module in China of 2019	88.19% CED	not specified	not specified	5.23% CO2; 6.80% CED	0.04% CED	4.97% CED; 2.52% CO2	not specified
97	Li et al.	2022	A comprehensive life cycle assessment study of innovative bifacial photovoltaic applied on building	82% CED; 82% CO2	not specified	2.4% CED; 2.4% CO2	5.95% CED; 5.95% CO2	not specified	not specified	not specified
98	Held and Ilg	2011	Update of environmental indicators and energy payback time of CdTe PV systems in Europe	not specified	35% CED; 40% CO2	not specified	not specified	not specified	6.38% CED; 7% CO2	*-7,36% CED; -99.91% CO2
99	Resalati et al.	2022	Life cycle assessment of different chalcogenide thin-film solar cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
100	Pallas et al.	2020	Life cycle assessment of emerging technologies at the lab scale: The case of nanowire-based solar cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
101	Tsang et al.	2016	A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
102	Celik et al.	2016	Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab	not specified	not specified	not specified	not specified	not specified	not specified	not specified
103	Krebs-Moberg et al.	2021	Third generation of photovoltaic panels: A life cycle assessment	not specified	not specified	not specified	not specified	not specified	not specified	*-16.55% CO2
104	Błaszczyk et al.	2021	Environmental performance of dye-sensitized solar cells based on natural dyes	not specified	not specified	not specified	not specified	not specified	not specified	not specified

Number	Author	Year	Title	Modules manufacturing	BOS manufacturing	Transportation	Installation	Use	End-of-Life	End-of-Life benefits
105	Hengevoss et al.	2016	Life Cycle Assessment and eco-efficiency of prospective, flexible, tandem organic photovoltaic module	not specified	not specified	not specified	not specified	not specified	not specified	not specified
106	Correa Guerrero et al.	2021	Energy performance of perovskite solar cell fabrication in Argentina. A life cycle assessment approach	not specified	not specified	not specified	not specified	not specified	not specified	not specified
107	Zhang et al.	2022	Techno-economic and environmental sustainability of industrial-scale productions of perovskite solar cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
108	Jia et al.	2021	Life cycle assessment on PERC solar modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
109	Espinosa et al.	2015	Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective	not specified	not specified	not specified	not specified	not specified	not specified	not specified
110	Wong et al.	2016	Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
111	Carneiro et al.	2022	Energy consumption and carbon footprint of perovskite solar cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
112	Sarialtin et al.	2021	Environmental assessment of transparent conductive oxide-free efficient flexible organo-lead halide perovskite solar cell	not specified	not specified	not specified	not specified	not specified	not specified	not specified
113	Ahangharnejhad et al.	2020	Environmental Impact per Energy Yield for Bifacial Perovskite Solar Cells Outperforms Crystalline Silicon Solar Cells	not specified	not specified	not specified	not specified	not specified	not specified	not specified
114	Zahedi et al.	2022	Environmental and damage assessment of transparent solar cells compared with first and second generations using the LCA approach	not specified	not specified	not specified	not specified	not specified	not specified	not specified
115	Reich et al.	2011	Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options	not specified	not specified	not specified	not specified	not specified	not specified	not specified
116	Lizin et al.	2013	Life cycle analyses of organic photovoltaics: A review	not specified	not specified	not specified	not specified	not specified	not specified	not specified
117	Salameh et al.	2020	Life cycle analysis comparison between single crystalline solar cells and poly crystaline gallium in UAE	not specified	not specified	not specified	not specified	not specified	not specified	not specified
118	Kim and Fthenakis	2011	Comparative life-cycle energy payback analysis of multi-junction a-SiGe and nanocrystalline/a-Si modules	not specified	not specified	not specified	not specified	not specified	not specified	not specified
119	Hong et al.	2016	Life cycle assessment of multicrystalline silicon photovoltaic cell production in China	not specified	not specified	not specified	not specified	not specified	not specified	not specified
120	Yang et al.	2015	Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade	not specified	not specified	not specified	not specified	not specified	not specified	not specified
121	Agostini et al.	2021	Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment	not specified	not specified	not specified	not specified	not specified	not specified	not specified
122	Serrano-Lujan et al.	2017	The greenest decision on photovoltaic system allocation	not specified	not specified	0.3% CO2	not specified	not specified	not specified	not specified
123	De Lima et al.	2021	The role of national energy policies and life cycle emissions of pv systems in reducing global net emissions of greenhouse gases	not specified	not specified	not specified	not specified	not specified	not specified	not specified
124	Zarzavilla et al.	2022	Comparison of Environmental Impact Assessment Methods in the Assembly and Operation of Photovoltaic Power Plants: A Systematic Review in the Castilla—La Mancha Region	not specified	not specified	not specified	not specified	not specified	2.6% CO2; 0.9% CED	not specified
125	Choi et al.	2021	Combined land use of solar infrastructure and agriculture for socioeconomic and environmental co-benefits in the tropics	not specified	not specified	not specified	not specified	not specified	not specified	not specified
126	Pascaris et al.	2021	Life cycle assessment of pasture-based agrivoltaic systems: Emissions and energy use of integrated rabbit production	not specified	not specified	not specified	not specified	not specified	not specified	not specified
127	Leon and Isihara	2018	Assessment of new functional units for agrivoltaic systems	not specified	not specified	not specified	not specified	not specified	not specified	not specified
128	Leon and Isihara	2018	Influence of allocation methods on the LC-CO2 emission of an agrivoltaic system	not specified	not specified	not specified	not specified	not specified	not specified	not specified
129	Mukisa et al.	2021	Multi criteria analysis ranking of solar photovoltaic modules manufacturing countries by an importing country: A case of Uganda	not specified	not specified	not specified	not specified	not specified	not specified	not specified

Appendix A.3: CED for Modules manufacturing

Technology	CED [MJ/M2]	Source author	Source title	Other
Monocrystalline	4415	Liu and van der Bergh	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	Indicated in a chart
Monocrystalline	3746	de wild Scholten	Energy payback time and carbon footprint of commercial photovoltaic systems	Values obtained as sum of values indicated composing the modules manufacturing
Monocrystalline	4560	de wild Scholten	Energy payback time and carbon footprint of commercial photovoltaic systems	Values obtained as sum of values indicated composing the modules manufacturing
Monocrystalline	3986	Ito et al.	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant	Cited
Monocrystalline	6100	Akinyele et al.	Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria	Cited
Monocrystalline	3867	Ito et al.	Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world	Cited
Monocrystalline	4750	Ludin et al.	Environmental impact and levelised cost of energy analysis of solar photovoltaic systems in selected asia pacific region: A cradle-to-grave approach	Cited
Monocrystalline	2600	Leccisi and Fthenakis	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV	Indicated in a chart
Monocrystalline	4490	Soares et al.	LCA study of photovoltaic systems based on different technologies	Cited
Monocrystalline	6829	Garcia-valverde et al.	Life cycle analysis of organic photovoltaic technologies	Cited
Monocrystalline	4938	Li et al.	A comprehensive life cycle assessment study of innovative bifacial photovoltaic applied on building	Cited
Monocrystalline	1949	Fthenakis and Leccisi	Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends	Indicated in a chart
multicrystalline	2982	Liu and van der Bergh	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	Indicated in a chart
multicrystalline	2088	de wild Scholten	Energy payback time and carbon footprint of commercial photovoltaic systems	Values obtained as sum of values indicated composing the modules manufacturing
multicrystalline	2524	de wild Scholten	Energy payback time and carbon footprint of commercial photovoltaic systems	Values obtained as sum of values indicated composing the modules manufacturing
multicrystalline	2737	Ito et al.	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant	Cited
multicrystalline	1816	Fthenakis and Leccisi	Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends	Indicated in a chart
multicrystalline	4600	Akinyele	Environmental performance evaluation of a grid-independent solar photovoltaic power generation (SPPG) plant	Cited
multicrystalline	2784	Sumper et al.	Life-cycle assessment of a photovoltaic system in Catalonia (Spain)	Cited
multicrystalline	2720	Wu et al.	Review on Life Cycle Assessment of Energy Payback of Solar Photovoltaic Systems and a Case Study	Values obtained as sum of values indicated composing the modules manufacturing
multicrystalline	3072	Ito et al.	Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world	Cited
multicrystalline	4070	Ludin et al.	Environmental impact and levelised cost of energy analysis of solar photovoltaic systems in selected asia pacific region: A cradle-to-grave approach	Cited
multicrystalline	3559	Soares et al.	LCA study of photovoltaic systems based on different technologies	Cited
cdte	2031	Garcia-valverde et al.	Life cycle analysis of organic photovoltaic technologies	Cited
cdte	1083	Ito et al.	Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world	Cited
cdte	1761	Serrano-Lujan et al.	The greenest decision on photovoltaic system allocation	Cited
cdte	1396	Liu and van der Bergh	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	Indicated in a chart
cdte	857	Leccisi and Fthenakis	Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV	Indicated in a chart
CIS	1600	Liu and van der Bergh	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	Indicated in a chart
CIS	1105	Ito et al.	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant	cited
CIS	2035	Ito et al.	Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world	Cited
CIS	2109	Soares et al.	LCA study of photovoltaic systems based on different technologies	Cited
CIS	3107	Garcia-valverde et al.	Life cycle analysis of organic photovoltaic technologies	Cited
a-Si	1550	Liu and van der Bergh	Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA	Cited
a-Si	1060	de wild Scholten	Energy payback time and carbon footprint of commercial photovoltaic systems	Values obtained as sum of values indicated composing the modules manufacturing
a-Si	1210	Ito et al.	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant	Cited
a-Si	847	Kittner et al.	An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand	Cited
a-Si	1394	Soares et al.	LCA study of photovoltaic systems based on different technologies	Cited
a-Si	1110	Garcia-valverde et al.	Life cycle analysis of organic photovoltaic technologies	Cited

List of Figures

Figure 1: Share of PV modules production by technology (17). 3

Figure 2: Global cumulative installed PV capacity by segment (19). 4

Figure 3: Cumulative PV capacity installed by country as of the end of 2021 (14)... 5

Figure 4: Additional PV capacity installed by country in 2021 (14). 5

Figure 5: CO_2 emission from PV manufacturing globally and share of PV manufacturing in total energy-related emission (right axis) (32). 7

Figure 6: Land occupation for selected technologies (16). 9

Figure 7: Median of water consumption over the full life cycle for selected technologies (44). 11

Figure 8: Process of selection of the relevant contributions (Own production). 20

Figure 9: Contributions analyzed by year of publication (Own production). 21

Figure 10: Most frequently applied functional units in the literature analyzed (Own production) 23

Figure 11: Types of data sources used in the literature analyzed (Own production). 25

Figure 12: Comparison between the year of publication of papers and the version of Ecoinvent applied (Own production). 26

Figure 13: Appearances of selected metrics in the literature analyzed (Own production). 27

Figure 14: Most frequently applied impact methodologies in the literature analyzed (Own production). 28

Figure 15: Inclusion of the lifecycle phases in the literature analyzed (Own production). 30

Figure 16: Most frequently adopted software in the literature analyzed (Own production). 32

Figure 17: Most frequent modules manufacturing locations in the literature analyzed (Own production). 34

Figure 18: Location of BOS components manufacturing in the literature analyzed (Own production). 35

Figure 19: Most frequent BOS manufacturing locations in the literature analyzed (Own production). 36

Figure 20: Most frequent installation locations in the literature analyzed (Own production). 36

Figure 21: Number of appearances of PV generations in the literature analyzed (Own production). 37

Figure 22: Number of appearances of the different PV technologies in the literature analyzed (Own production). 38

Figure 23: Installation configurations encountered in the literature analyzed (Own production). 39

Figure 24: Module efficiencies encountered in the literature analyzed (Own production). 41

Figure 25: Lifetime for modules of first and second generation encountered in the literature analyzed (Own production). 43

Figure 26: CED and $CO_{2\text{-eq}}$ emissions from the modules manufacturing phase in percentage with respect to the impact of the full life cycle (Own production). 48

Figure 27: CED and $CO_{2\text{-eq}}$ emissions from the BOS manufacturing phase in percentage with respect to the impact over the full life cycle (Own production)... 51

Figure 28: CED and $CO_{2\text{-eq}}$ emissions from the transportation phase in percentage with respect to the impact over the full life cycle (Own production). 54

Figure 29: CED and $CO_{2\text{-eq}}$ emissions from the installation phase in percentage with respect to the impact over the full life cycle (Own production). 56

Figure 30: CED and $CO_{2\text{-eq}}$ emissions from the use phase in percentage with respect to the impact over the full life cycle (Own production). 59

Figure 31: CED and $CO_{2\text{-eq}}$ emissions from the end-of-life phase in percentage with respect to the impact over the full life cycle (Own production). 62

Figure 32: CED and $CO_{2\text{-eq}}$ emissions reduction from the benefits from end-of-life phase in percentage with respect to the impact over the full life cycle (Own production). 63

Figure 33: Values encountered in the literature for the cumulative energy demand for monocrystalline modules manufacturing (Own production). 73

Figure 34: Values encountered in the literature for the cumulative energy demand for multicrystalline modules manufacturing (Own production). 74

Figure 35: Values encountered in the literature for the cumulative energy demand for CdTe modules manufacturing (Own production). 75

Figure 36: Values encountered in the literature for the cumulative energy demand for CIS modules manufacturing (Own production). 75

Figure 37: Values encountered in the literature for the cumulative energy demand for a-Si modules manufacturing (Own production). 76

Figure 38: CED results for monocrystalline technology (Own production). 120

Figure 39: GWP results for monocrystalline technology (Own production). 122

Figure 40: EPBT results for monocrystalline technology (Own production). 123

Figure 41: CO_2PBT results for monocrystalline technology (Own production). ... 124

Figure 42: CED results for multicrystalline technology (Own production). 125

Figure 43: GWP results for multicrystalline technology (Own production). 126

Figure 44: EPBT results for multicrystalline technology (Own production). 128

Figure 45: CO_2PBT results for multicrystalline technology (Own production). 128

Figure 46: CED results for a-Si technology (Own production). 129

Figure 47: GWP results for a-Si technology (Own production). 131

Figure 48: EPBT results for a-Si technology (Own production). 132

Figure 49: CO_2PBT results for a-Si technology (Own production). 133

Figure 50: CED results for CIS technology (Own production). 134

Figure 51: GWP results for CIS technology (Own production). 135

Figure 52: EPBT results for CIS technology (Own production). 137

Figure 53: CO_2PBT results for CIS technology (Own production). 137

Figure 54: CED results for CdTe technology (Own production). 138

Figure 55: GWP results for CdTe technology (Own production). 139

Figure 56: EPBT results for CdTe technology (Own production). 141

Figure 57: CO_2PBT results for CdTe technology (Own production). 141

Figure 58: CED results for OPV technology (Own production). 142

Figure 59: GWP results for OPV technology (Own production). 144

Figure 60: EPBT results for OPV technology (Own production). 145

Figure 61: CO_2PBT results for OPV technology (Own production). 145

Figure 62: Comparisons of CED results of scenarios over the technologies (Own production). 146

Figure 63: Comparisons of CED results of technologies over the scenarios (Own production). 147

Figure 64: Comparisons of GWP results of scenarios over the technologies (Own production). 148

Figure 65: Comparisons of GWP results of technologies over the scenarios (Own production). 149

Figure 66: Comparisons of EPBT results of scenarios over the technologies (Own production). 150

Figure 67: Comparisons of EPBT results of technologies over the scenarios (Own production). 151

Figure 68: Comparisons of CO_2PBT results of scenarios over the technologies (Own production). 152

Figure 69: Comparisons of CO_2PBT results of technologies over the scenarios (Own production). 153

Figure 70: Sensitivity analysis of the CED with respect to irradiation (Own production). 155

Figure 71: Sensitivity analysis of the GWP with respect to irradiation (Own production). 156

Figure 72: Sensitivity analysis of the EPBT with respect to irradiation (Own production). 157

Figure 73: Sensitivity analysis of the CO_2PBT with respect to irradiation (Own production). 158

Figure 74: Sensitivity analysis of the CED with respect to modules conversion efficiency (Own production). 160

Figure 75: Sensitivity analysis of the GWP with respect to modules conversion efficiency (Own production). 160

Figure 76: Sensitivity analysis of the EPBT with respect to modules conversion efficiency (Own production). 161

Figure 77: Sensitivity analysis of the CO_2PBT with respect to modules conversion efficiency (Own production). 162

Figure 78: CED with inclusion of benefits from the end-of-life (Own production). 163

Figure 79: Comparison of the CED in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production). 164

Figure 80: GWP with inclusion of benefits from the end-of-life (Own production). 165

Figure 81: Comparison of the GWP in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production). 166

Figure 82: Comparison of the EPBT in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production). 167

Figure 83: Comparison of the CO_2PBT in scenarios with and without the benefits from the end-of-life and percentage reduction (right axis) (Own production). 169

List of Tables

Table 1: PV segmentation by size (20). 5

Table 2: Steps composing the LCIA phase (52). 14

Table 3: Impact categories included in ReCiPe methodology (89). 29

Table 4: Example of a segmentation of solar irradiation (82) (125) (23). 42

Table 5: Values of parameters for the selected technologies (Own production). 72

Table 6: Specific cumulative energy demand in modules manufacturing phase (Own production). 77

Table 7: Specific modules weight of the PV technologies considered (Own production). 83

Table 8: Specific emission factors for the transport modes considered (186). 84

Table 9: Values applied in the evaluation framework for the cumulative energy demand of the end-of-life phase (Own production). 99

Table 10: Input variables of the evaluation framework (Own production). 104

Table 11: Impact indicators of the evaluation framework (Own production). 106

Table 12: Common input variables across all scenarios considered (Own production). 115

Table 13: Mixed supply scenario’s specific input variables (Own production). 116

Table 14: Chinese supply scenario’s specific input variables (Own production). 116

Table 15: Out-of-Asia supply scenario’s specific input variables (Own production). 117

Table 16: German supply scenario’s specific input variables (Own production). 118

Table 17: Italian supply scenario’s specific input variables (Own production). 119

Table 18: Mixed supply scenario’s input variables (Own production). 154

Table 19: Modules conversion efficiencies in the reference scenario (Own production). 159

List of Acronyms

AC	Alternating current
a-Si	Amorphous silicon
BAPV	Building applied photovoltaic
BIPV	Building integrated photovoltaic
BOS	Balance of system
CAGR	Compound annual growth rate
CdTe	Cadmium telluride
CED	Cumulative energy demand
CIGS	Copper-indium-gallium-selenide
CIS	Copper-indium-selenide
$CO_{2\text{-eq}}$	CO_2 equivalent
CO_2PBT	CO_2 payback time
COP	Conference of the Parties
c-Si	Crystalline silicon
CSP	Concentrated solar power
DC	Direct current
DSSC	Dye sensitized solar cells

EoL	End-of-life
EPBT	Energy payback time
EVA	Ethylene vinyl acetate
FRELP	Full Recycling EoL Procedure
FU	Functional unit
GHG	Greenhouse gases
GWP	Global warming potential
IEA	International Energy Agency
ILCD	International Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NECP	National Energy and Climate Plan
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OPV	Organic photovoltaic
PEF	Product Environmental Footprint
PV	Photovoltaic
R&D	Research and Development

RESIELP	Recovery of Silicon and other materials from the End-of-life Photovoltaic Panels
RQ	Research question
VIPV	Vehicle integrated photovoltaic
WEEE	Waste Electrical and Electronic Equipment
WHO	World Health Organization

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