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D1.7 Key Sustainable Indicators (KSI) based on LCA for high PV penetration scenarios.

T1.6 Specific Key Sustainable Indicators (KSI) based on LCA for high PV penetration scenarios

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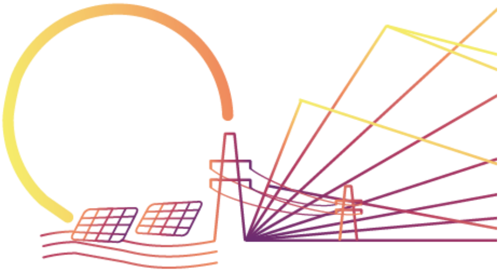

Summary

Deliverable 1.7 of the SERENDI-PV project has evaluated the environmental performance of innovative photovoltaics (PV) technologies, including floating, bifacial, and BIPV, compared to conventional monofacial and BAPV technologies. The report has assessed their sustainability and impact on the penetration of solar PV in the power grids of Finland, Germany, and Spain for 2022, 2030 and 2050. It has identified hotspot lifecycle stages for potential optimizations to reduce environmental impacts and compares installation scenarios across different regions and time horizons.

Key sustainability indicators (KSI) have been defined to monitor the integration and penetration of PV systems into the grid, and a sensitivity analysis has explored the impact of varying performance ratios on lifecycle assessments.

Deliverable 1.7, an output of task T1.6, has provided insights into the potential environmental benefits of integrating innovative PV technologies into power grids. It emphasizes strategic planning and geographic considerations to maximize these benefits, offering valuable information for stakeholders and policymakers aiming to promote sustainable energy practices in Europe and beyond.

Document Information

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Disclaimer

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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

Deliverable 1.7 of the SERENDI-PV project presents a detailed assessment of the environmental performance of innovative photovoltaics (PV) technologies, focusing on their integration into the power grids of Finland, Germany, and Spain from 2022 to 2050. The report evaluates the sustainability and impact of PV technologies such as floating, bifacial (ground-mounted), and BIPV (façade) in comparison to conventional monofacial (ground-mounted) and BAPV (rooftop) technologies. In addition, the hotspot analysis identifies critical stages in the lifecycle of these innovative technologies where optimizations could significantly reduce environmental impacts.

The deliverable includes a comparative analysis of PV system installations across different geographic regions and time horizons, providing valuable insights into their environmental performance. Key sustainability indicators (KSI) have been defined to monitor the integration of PV systems and their penetration into the power grid, offering a comprehensive view of both innovative and conventional PV technologies' environmental impacts.

Additionally, a sensitivity analysis has been conducted to assess variations in performance ratios, a crucial Key Performance Indicator (KPI), to better understand their influence on Life cycle Assessment (LCA) related to the developed technologies.

Beyond this, the future-oriented life cycle assessment, or prospective life cycle assessment (pLCA), of solar photovoltaic technologies has been thoroughly scrutinized in light of the particular solar PV technologies chosen for this project. The main findings indicate that the current pLCA tools do not consider emerging or high TRL level solar PV technologies; rather, they concentrate on the technologies that have either withdrawn from the market and/or have a very small market share in the total PV production volume. Thus, derived life cycle inventories for emerging solar PV technologies provides significant contribution to the pLCA community, which is in its early stages.

In conclusion, Deliverable 1.7 underscores the significant potential of innovative PV technologies to mitigate environmental impacts compared to traditional technologies. It emphasizes the importance of strategic planning and geographical considerations in maximizing the environmental benefits of PV systems. These findings are essential for informing policymakers and stakeholders involved in advancing sustainable energy practices in Europe and globally.

1.2 Reference material

No applicable

1.3 Relation with other activities in the project

Table 1.1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within SERENDI-PV project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1: Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
WP1	The current deliverable feeds from WP1 activities.

1.4 Abbreviation list

Table 1.2: Abbreviation list

Abbreviation	Name
AC	Acidification
ADe	Resource use, minerals and metals
ADf	Resource use, fossils
BAPV	Building Attached / Applied photovoltaics
BIPV	Building Integrated photovoltaics
CFC	Chlorofluorocarbon
EF	Environmental Footprint
EoL	End of life
EU	European Union
FEP	Eutrophication – freshwater
FU	Functional unit
GHG	Greenhouse gas
GLO	Global
GW	Climate change
HCFC	Hydrochlorofluorocarbon
HTc	Human toxicity, cancer
HTnc	Human toxicity, non-cancer
ILCD	International Reference Life Cycle Data System Handbook
IR	Ionizing irradiation
ISO	International Organization for Standardization
KSIs	Key Sustainable Indicators
LCA	Life cycle assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land use
Mc	Monocrystalline
MEP	Eutrophication, marine
OD	Ozone depletion
PEF	Product Environmental Footprint
pLCA	Prospective life cycle assessment
PM	Particulate matter
POF	Photochemical ozone formation
PR	Performance ratio
PV	Photovoltaics
Rest of word	RoW

TEP	Eutrophication - terrestrial
VOCs	Volatile organic compounds
WU	Water use
MEP	Eutrophication – marine

2 INTRODUCTION

During the Paris Summit (2015), or Conference of the Parties 21 (COP21), the Paris Agreement was signed, in which world leaders committed to combating climate change. The main objective of this agreement was to limit the rise in global temperature to less than 2°C, with efforts to keep it below 1.5°C compared to the pre-industrial age. However, during COP28 (2023), it was revealed that the goals set at COP21 were far from being met, highlighting that developing countries need viable, effective, and low-cost mitigation options across all sectors. To limit global warming to 1.5°C, global greenhouse gas (GHG) emissions must be reduced by 43% by 2030 and 60% by 2035 compared to 2019, aiming to achieve net zero CO_2 emissions by 2050. During these meetings, the fundamental role of renewable energy in mitigating the impacts of climate change and promoting a transition towards a low-carbon economy was highlighted. In addition, a report by the European Commission highlights that the transition towards renewable energies in the European Union not only enhances energy security and generates significant savings but has also reduced the annual consumption of fossil fuels by 13% since 2005. This transition was instrumental in preventing an 11% increase in GHGs in 2018, contributing to the achievement of emission reduction targets. While the energy-intensive industrial sector has spearheaded this transformation, challenges persist in decarbonizing other sectors [1]. In this sense, solar PV (PV) technology has become an essential option among renewable energy sources due to its abundant availability, scalability, and decreasing costs.

Solar PV represents a clean and renewable energy source that is fundamental in transitioning towards a more sustainable and environmentally friendly energy system [2]. Over the past decade, solar PV has become cost-competitive in several European markets, reaching, together with wind energy, a 60% share in renewable electricity generation in 2022, up from 24% in 2010. Furthermore, solar and wind energy generation has been projected to reach nearly 50% of gross electricity production by 2030. Achieving this would require an average annual increase of 111 TWh in Variable Renewable Energy generation, nearly three times the annual growth recorded between 2010 and 2022 (+38 TWh per year) [3]. This rapid growth of renewable energy sources since 2005 has enabled the EU to reduce the use of fossil fuels and associated GHG emissions by 145 Mtep (millions of tonnes equivalent to petroleum) and 478 Mt of CO_2, respectively, in 2018 [4].

Solar PV is used in two ways, each with its characteristics and applications: through the solar thermal and electricity routes. The solar thermal route uses the sun's heat through various devices, such as solar collectors, solar water heaters and solar dryers. These devices capture solar radiation and convert it into thermal energy, which can be used for space heating, air conditioning, hot water, industrial process heat, drying, distillation and desalination, among other applications [5]. Solar thermal technology offers an efficient and sustainable solution for heating, cooling and thermal processing needs in various sectors [6]. On the other hand, the solar electricity route, also known as PV, uses PV cells to convert sunlight into electricity directly [7]. These cells, made of semiconductor materials such as silicon, generate an electrical current when exposed to solar radiation. PV systems can vary in size and scale, from small individual solar panels installed on residential rooftops to large utility-scale solar plants. This technology offers a clean and efficient way to produce electricity without generating GHGs or other pollutants during its operation [2].

Furthermore, PV systems present several advantages, such as low cost and operational flexibility. They are modular, meaning they can be easily adapted to different applications and scaled to the specific needs of each project. They also have lower operation and maintenance costs than other energy sources since they do not require fuel and have a long life with little maintenance. This modular capability and efficiency make solar PV an attractive option for a wide range of applications, from distributed generation systems to large commercial or industrial-scale solar installations. In addition to the fact that solar thermal and PV energy represent versatile and sustainable solutions for producing clean and renewable energy, they contribute significantly to climate change mitigation [2,8].

Additionally, advances such as floating panels, bifacial modules, and building-integrated photovoltaics systems (BIPV) have expanded the range of solar PV applications. These innovations have represented significant progress in making solar PV more versatile and accessible. These advances have offered new perspectives for sustainable development by increasing efficiency and effectiveness while reducing environmental impact [9–12].

Life Cycle Assessment (LCA) has emerged as an essential tool to comprehensively evaluate the environmental impacts of all products, processes and services, including PV systems. More generally, LCA has allowed stakeholders to identify potential critical points in terms of environmental impact, from the extraction of raw materials through manufacturing, transportation, installation, operation and disposal at the end of their useful life [13–15].

At a more specific level, LCA could provide a comprehensive view of environmental impacts throughout the entire life cycle of PV systems. This detailed information could allow PV system manufacturers, installers, and users to make informed decisions to optimize resource use, minimize environmental impacts, and reduce the environmental footprint associated with solar PV deployment [16].

In the context of high PV penetration scenarios, integrating LCA-based Key Sustainability Indicators (KSIs) has become important to assess the environmental sustainability of renewable energy transitions. These indicators play an important role in evaluating the environmental performance of solar PV systems, allowing stakeholders to make informed decisions and formulate effective policies. By covering several factors, including environmental footprint, GHG emissions, solid waste generation, water use, land occupation and the ratio of renewable and non-renewable energy in the energy mix, the KSIs could provide a holistic framework for evaluating the environmental sustainability of solar PV deployment strategies.

This deliverable explores the concept of KSIs based on LCA in PV penetration scenarios, with a comprehensive focus on various aspects of solar PV technology. To achieve this goal, a hotspot analysis of the LCA has been conducted to identify stages in the life cycle of floating PV systems, ground-mounted bifacial systems, and BIPV where optimizations can be made to reduce environmental impact. Additionally, a comparative analysis has been performed between utility-scale systems (bifacial and floating vs. monofacial ground-mounted) and small-scale systems (BIPV and Building Applied photovoltaics (BAPV)) to gain a thorough understanding of the environmental and sustainability implications of each implementation method.

Furthermore, an environmental analysis has been conducted to assess the environmental performance of PV system penetration in the power grids of Finland, Germany, and Spain, with projections for 2022, 2030, and 2050. Based on the results obtained, several KSIs relevant to PV systems from a sustainability perspective have been identified and analysed.

Regarding the innovations developed in the project, an environmental analysis has been performed to determine their effects through a sensitivity analysis, varying the performance ratio (PR). This comprehensive approach offers a holistic view of the challenges and opportunities associated with the widespread integration of solar PV energy, thus contributing to the development of more sustainable energy policies and the promotion of renewable energy.

Furthermore, the examination of the literature regarding the use of pLCA on developing solar PV technologies revealed that none of the pLCA tools currently in use adequately address these technologies; instead, they concentrate on solar PV technologies that are either no longer in use or make up a very small portion of the world's total photovoltaic production volume. Therefore, it is anticipated that the concept of KSIs based on LCA in PV penetration scenarios will greatly benefit the pLCA community as well as the development of pLCA analysis tools.

3 METHODOLOGICAL APPROACH

The LCA methodology is utilized to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle. This involves assessing the relevant inputs and outputs in terms of mass and energy balance. Transparency in applying the LCA methodology is ensured through adherence to established standards, primarily provided by the International Organization for Standardization (ISO). These standards include:

- ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework [15].
- ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines (ISO14044, 2006).

The execution of an LCA involves four key phases, each of which is essential for comprehensive analysis (**Figure 3.1**).

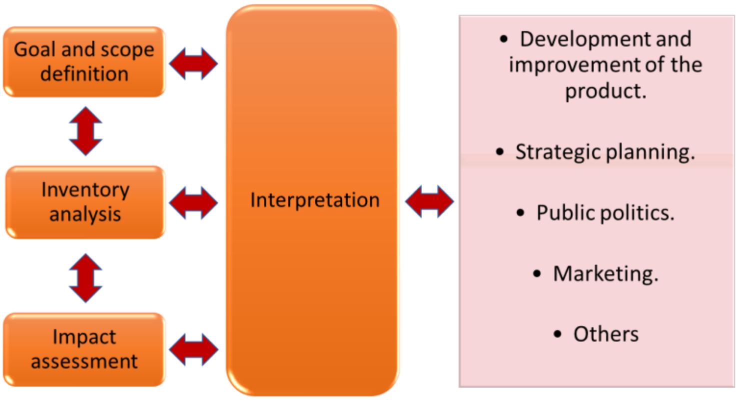


Figure 3.1: Life cycle assessment diagram: methodology phases and application [14]

1. **Goal and scope definition**:
    - ***Objective Setting***. In this step, the purpose of the LCA study is clearly defined. The LCA analysis could include evaluating the environmental performance of a product, process or service, comparative analysis or identifying possible hotspots for improvement.
    - ***Stakeholder Identification***. The audience or interested parties that could be interested in the study are identified, considering the document's privacy.
    - ***Scope definition***. The limits of the evaluation are defined, determining which aspects of the product, process or service will be included and excluded. This involves defining the functional unit (FU), system boundaries, allocation rules, and cut-off criteria. Additionally, the assumptions made during the study and the limitations must be documented to ensure transparency and help interpret results accurately.
2. **Inventory analysis**:
    - ***Data collection***. Detailed information is collected on inputs (such as raw materials, energy and water), outputs (products, emissions and waste) and processes throughout the product's life cycle, process or service being implemented.
    - ***Life Cycle Inventory (LCI).*** Collected data is organized and structured into a comprehensive inventory, often using standardized formats and databases to ensure consistency and comparability. The LCI must refer to either the reference unit or the FU.

3. **Impact evaluation**:
    - ***Impact categories selection***. Relevant impact categories are identified and selected based on the goal and scope of the study, which may include climate change, resource depletion, acidification, eutrophication, among others.
    - ***Impact quantification***. Potential environmental impacts associated with the inventory data collected in the previous phase are assessed, often using impact assessment methods.
    - ***Normalization and weighting***. As an optional step in presenting the results, they can be normalized or weighted to facilitate comparison and aggregation between different impact categories.
4. **Results interpretation:**
    - ***Results analysis***. The results of the LCA are analysed and interpreted to extract significant ideas and conclusions about the environmental performance of the product, process or service.
    - ***Sensitivity analysis***. Where necessary, an assessment of the sensitivity of the results to key assumptions, parameters and uncertainties can be carried out to assess the robustness of the findings. This step is optional.
    - ***Conclusions and recommendations***. Key findings from the LCA study are summarized and recommendations are provided to improve the environmental performance of the product, process or service, as well as guide decision-making and future actions.

Each phase of the LCA process is interconnected and builds on the previous one, ultimately leading to a comprehensive understanding of the environmental impacts and sustainability implications of the evaluated product, process or service.

3.1 Goal of the study

3.1.1 Intended applications

In the context of the SERENDI-PV project, the goal definition process has been crucial as it underpins the entire sustainability assessment of PV systems. To ensure the rigor and coherence of this evaluation, the project adopts a systematic approach, adhering to ISO14040, (2006) and ISO14044, (2006) standards, thus guaranteeing coherence, transparency and reliability in the evaluation process.

Within the SERENDI-PV project, the main objective of the LCA analysis has been to evaluate the sustainability of the penetration of PV systems in the power grid. This has encompassed not only the environmental implications of the technologies alone but also the implications that integrating these technologies into the grid would have. This environmental study must remain closely aligned with the overall objective of the SERENDI-PV project, which seeks to advance renewable energy technologies and encourage their widespread adoption.

In this sense, an analysis of hotspots for innovative technologies (floating, bifacial and BIPV) has been carried out to identify the critical points of the technology and thus identify which part of the system optimizations could be made to reduce environmental impacts. This assessment has gone deeper into identifying the environmental impact of the full life cycle of each technology, from manufacturing and installation to operation and end-of-life management. This approach has enabled a comprehensive assessment of sustainability implications at various stages of the technology life cycle.

Furthermore, the evaluation has also focused on comparing innovative PV technologies, such as floating, bifacial and BIPV, with conventional technologies, such as monofacial and BAPV. In addition, the evaluation has considered different scenarios to identify the various contexts in which these technologies can be implemented. In this sense, the implementation of PV systems in Spain, Germany and Finland has been examined. Through this analysis, the influence of geographical and climatic factors on sustainability results has been recognized. In addition, scenarios have been projected in different time horizons (2022, 2030 and 2050), considering the dynamic nature of technological progress over time.

Another important task in this work has been to establish the main KSIs based on the LCA methodology. These indicators have served as metrics to measure the environmental performance of integrating PV systems into the grid. By defining and measuring these KSIs, the analysis has aimed to provide tangible evidence of the environmental impact obtained (positive or negative) by the innovative technologies that have been explored. These results could increase trust among stakeholders and drive the implementation of these sustainable energy solutions.

Finally, an environmental analysis has been conducted to evaluate the potential effects of the innovations developed in the SERENDI-PV project. This has been achieved through a detailed sensitivity analysis that varied the PR of the PV systems. By varying the PR, the study has evaluated how different system efficiency levels could influence the overall environmental impact. This approach provides a comprehensive understanding of how technological advances in the SERENDI-PV project could improve sustainability and reduce the environmental footprint of solar PV systems.

In conclusion, this analysis has focused on evaluating the sustainability of different innovative PV systems and their integrations into the power grid of various countries and in different time horizons. This holistic approach seeks to improve the acceptance of these innovative solutions as sustainable energy solutions.

3.1.2 Target audience

The LCA offers valuable insights into environmental impacts, supporting companies in making informed decisions regarding sustainability and monitoring progress over time. Therefore, identifying key stakeholders interested in sustainability outcomes is crucial.

The primary audience for the environmental assessment study comprises the SERENDI-PV project consortium and the European Commission. However, the LCA findings can also benefit a wider audience, including researchers, companies specializing in utility-scale PV system installation, the general public interested in the installation of personal PV systems for their own energy consumption, and authorities concerned with the environmental impact of these technologies. Sharing these results with diverse stakeholders promotes transparency and informed decision-making across various sectors.

3.2 Scope of the study

On the other hand, the scope should describe the detail and depth of the study. In this sense, during the definition of the scope of the analysis, the product/process/service under study is identified, all the limitations and assumptions are detailed, and the calculation method used to analyse environmental performance is defined. More specifically, the scope must provide information on the FU and the reference unit, a description of the system boundaries, limitations and assumptions, among others.

Furthermore, the entire scope should be defined according to previously published similar studies in the same field. This requirement must be considered to guarantee the comparability and reproducibility of the results in future research. In this sense, an extensive literature review has been carried out to identify the most common methodological approaches when defining the scope of LCA studies (see **Annex I: Bibliography review).** So far, 45 articles and other documents related to LCA analyses have been reviewed.

3.2.1 Functional unit

The selection of a FU is not a universal process. The FU may need to be adjusted according to the specific context and purpose of the LCA. To ensure that the choice of FU is relevant, reliable and robust, existing standards and guidelines should be consulted, such as ISO14040, (2006) and ISO14044, (2006), the Product

Environmental Footprint (PEF) [17] method or The International Reference Life Cycle Data System Handbook (ILCD) [18]. Furthermore, the FU must be meaningful and understandable to the general public using familiar, intuitive, and relatable units. On the other hand, FUs must be compatible with the data sources and flexible enough to adapt to parameter variations, limits and impacts. Selecting the appropriate FU for LCA is an essential step that affects the validity and credibility of the results and conclusions.

To select the FU for this analysis, the literature review and the project's objective have been considered. In this sense, only 48 of the 50 documents reviewed have the FU clearly defined. Furthermore, some documents refer to the use of more than one type of FU. **Figure 3.2** shows the distributions considering the selected FUs.

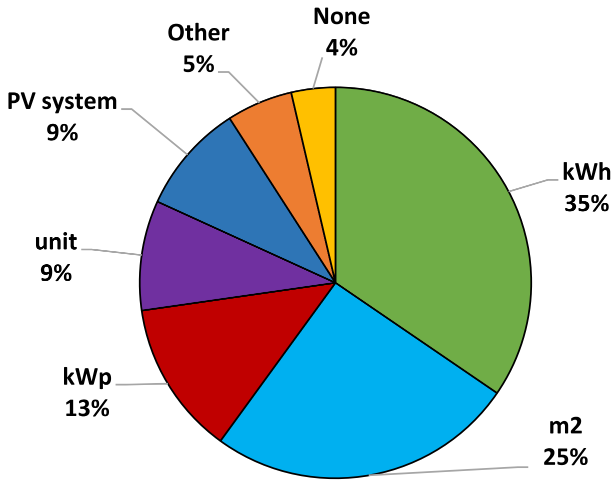


Figure 3.2: Functional unit (FU) selected in the reviewed documents.

The results (**Figure 3.2**) show that 19 of the reviewed documents considered the amount of energy (KWh) produced as FU. Using the amount of energy produced as FU in an LCA has been preferred because it provides a standardized and relevant measure to compare different technologies. On the other hand, 14 documents have used the surface in m^2, as FU. This FU has been preferred in studies that have focused mainly on the production of solar panels. Another FU used 7 times has been the kWp. On the other hand, the production of 1 unit or the installation of the entire PV plant has been considered in 5 papers as FU.

As mentioned above, the project's main objective has been to determine the environmental performance of energy production through PV systems and the impact of integrating those systems into the grid. Considering this, this study has found the production of 1 kWh of energy through the different PV systems to be a suitable FU. Using the amount of energy produced as FU, the system's energy efficiency can be evaluated. This also allows different systems to be compared regarding their environmental impact, which is essential for decision-making in the transition toward more sustainable and renewable energy sources. Furthermore, as seen in the reviewed literature, the amount of energy produced has been a common measure understood and used in the context of environmental assessment of PV systems, which facilitates comparison with other studies and communication of LCA results to different interested parties.

3.2.2 System boundaries

The definition of the system boundary is another fundamental aspect of the LCA methodology. This process determines which unit processes are included and evaluated throughout the analysis, thus establishing the scope of the evaluation. Delineation of the system boundary is based on several key factors, such as the desired end product, assumptions inherent to the study and limitations of available data.

System boundaries can be established in several ways, each focusing on the product life cycle stages. These limits can be described as follows (**Figure 3.3**):

- **Cradle-to-Gate**: This approach ranges from extracting raw materials to manufacturing the final product, including all necessary transformations and associated transportation. However, it excludes the use and disposal phases of the product.
- **Gate-to-Gate**: Here, the analysis focuses only on the stages of receiving raw materials and their transformation into the final product, omitting considerations on extracting raw materials and their disposal at the end of useful life.
- **Gate-to-Grave**: This approach extends from the production stage to the end of the product's useful life, covering the use and disposal phases but excluding the extraction of raw materials.
- **Cradle-to-Grave**: Enveloping the entire product life cycle, this approach includes everything from extraction, processing, distribution, use and disposal of raw materials until the end of their useful life.
- **Cradle-to-Cradle**: Similar to the Cradle-to-Grave approach, but with an emphasis on recycling and reusing materials at the end of the product's life.

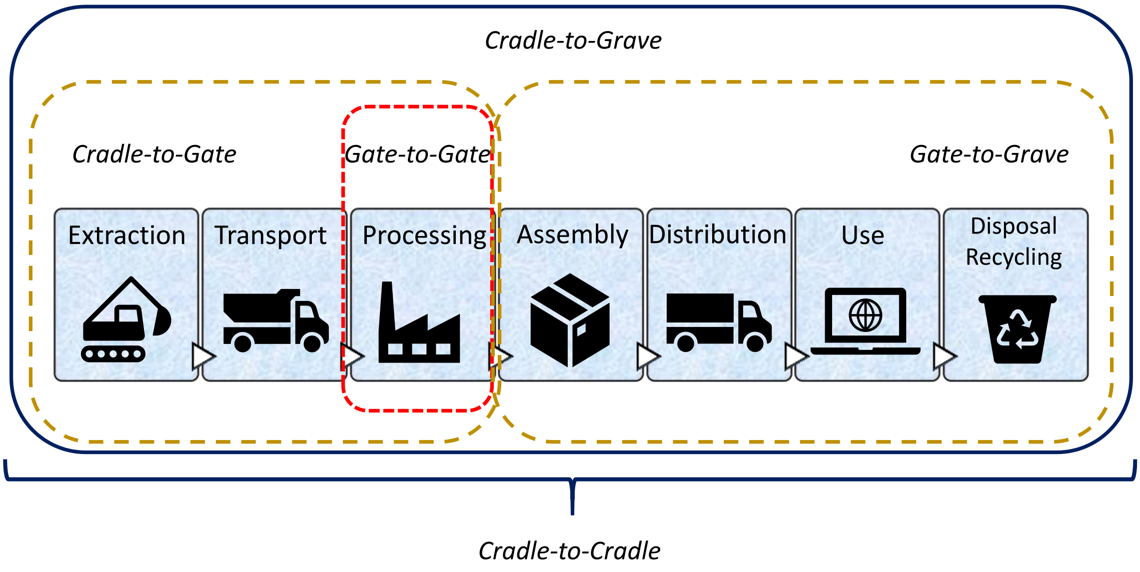


Figure 3.3: Different LCA approaches

The selection of the system boundary depends on the study objectives, data availability, and specific evaluation needs. By carefully delineating the system boundary according to these parameters, the LCA analysis effectively evaluates the environmental implications of the stages considered, facilitating informed decision-making and effective resource management.

To select the system boundary for this analysis, the literature review and the project's objective have been considered. In this sense, only 48 of the 50 documents reviewed have the system boundary clearly defined. Furthermore, some documents use more than one system boundary. **Figure 3.4** shows the distributions considering the selected system boundary.

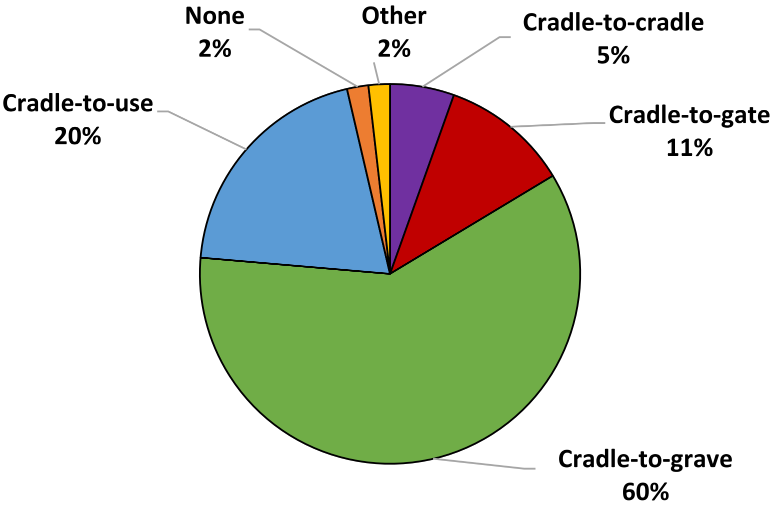


Figure 3.4: System boundary selected in the reviewed documents

The results (**Figure 3.4**) show that 33 of the reviewed documents have considered the cradle-to-grave approach as a system boundary. Considering cradle-to-grave system boundaries in the LCA for PV systems is crucial, as it provides a comprehensive perspective of environmental impacts, from raw material extraction to final disposal, enabling a more accurate assessment of their environmental footprint. On the other hand, 11 documents have used the cradle-to-use approach. Another system boundary used 6 times has been the cradle-to-gate. On the other hand, the cradle-to-cradle approach has been considered 3 times as a system boundary.

In **Figure 3.5**, the system boundary for the SERENDI-PV project has been presented:

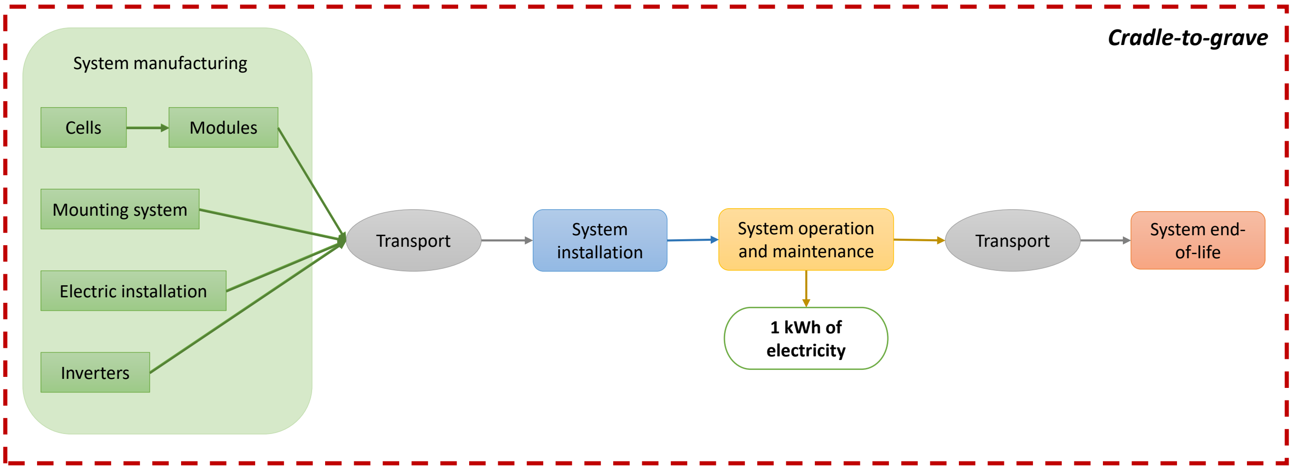


Figure 3.5: System boundaries for the SERENDI-PV project

As mentioned earlier, the main objective of this project has been to evaluate the environmental performance of energy production through PV systems and the implications of integrating these systems into the grid**.** In line with this objective, the study has opted to consider cradle-to-grave system boundaries. This means that the entire lifecycle of PV systems has been considered, from raw material extraction to final disposal. By employing cradle-to-grave system boundaries, the assessment encompasses all stages of the PV system's lifecycle, providing a comprehensive understanding of its environmental impact. This approach allows for a thorough evaluation of energy production efficiency and facilitates comparison among different systems.

As previously discussed, a comparative LCA analysis has been conducted between floating, ground-mounted bifacial, and ground-mounted monofacial systems (utility-scale systems). Additionally, comparisons have been made between BIPV and BAPV for small-scale systems. This comprehensive approach aims to assess the environmental performance of various PV technologies across different installation scenarios and scales and see which ones are more sustainable from an environmental point of view.

3.2.3 Technologies and description

To comprehensively assess the environmental impact of PV systems, it is essential to understand in detail the components that constitute them. Each element plays a critical role in the efficiency and sustainability of solar PV generation, from solar cells to inverters. Understanding these components is fundamental for conducting accurate and thorough LCA, which evaluates not only energy performance but also the environmental impacts associated with raw material extraction, manufacturing, transportation, installation, and decommissioning and disposal of the systems. In this sense, the main components that makeup PV systems are as [19,20]:

- **Solar Cells and Panels**: Solar cells are semiconductors that convert sunlight directly into electricity through the PV effect. Multiple solar cells are interconnected to form solar panels or modules. These panels are typically made of silicon-based cells, but emerging technologies may use materials like thin-film or perovskite. In floating PV systems, panels are designed to be waterproof and durable. Different types of panels can be used: bifacial panels (capturing sunlight from both sides) or monofacial panels (capturing sunlight from one side). In BIPV and BAPV systems, solar panels are integrated or adapted to building structures, serving dual purposes of generating electricity and providing architectural functionality.
- **Mounting Systems**: Mounting systems provide structural support for solar panels and ensure proper orientation and tilt angles for optimal sunlight exposure. In ground-mounted systems, mounting structures include racks or frames made of aluminium or steel, allowing for fixed-tilt or tracking configurations to maximize energy production. Floating PV systems use specialized floating structures to keep the panels afloat on water bodies, requiring innovative design considerations to ensure stability and durability in aquatic environments. BIPV and BAPV systems integrate panels directly into building elements, eliminating the need for separate mounting structures.
- **Electrical Installation**: Electrical installation encompasses various components and wiring necessary to connect the solar panels, inverters, and other system elements. This includes direct current wiring between panels, combiner boxes for consolidating multiple strings of panels, and alternating current wiring connecting the panels to inverters and the power grid or building loads. Floating PV systems may require special waterproofing measures for wiring. In BIPV and BAPV systems, electrical components are integrated within building structures to maintain aesthetics and functionality.
- **Inverters**: Inverters are critical components that convert the direct current electricity generated by solar panels into alternating current electricity suitable for use in homes, businesses, or the grid. Inverters come in various types, including string inverters, microinverters, and power optimizers, each offering different advantages in terms of system efficiency, scalability, and monitoring capabilities. In floating PV systems, inverters may need additional protection against water exposure. Bifacial and monofacial ground-mounted systems utilize inverters suitable for ground installations, such as string or microinverters. In BIPV and BAPV systems, inverters may be integrated into building structures or installed in limited spaces to maintain architectural integrity.

3.2.3.1 Floating PV system

Floating PV systems involve the installation of solar panels on floating structures placed on bodies of water such as lakes, reservoirs, or ponds. These systems are gaining popularity due to their versatility and numerous benefits.

One key advantage is land conservation. By utilizing bodies of water for solar PV generation, floating PV systems avoid the need for large areas of land, which can be scarce or valuable for other purposes such as agriculture or development. This makes them particularly attractive in densely populated areas with limited land availability. Moreover, floating PV systems offer environmental benefits. They can help reduce water evaporation from reservoirs, thereby conserving water resources, and also prevent algae growth by shading the water surface, which improves water quality [21]. In addition, the cooling effect of water can enhance the performance of solar panels, increasing their efficiency and lifespan.

Overall, floating PV technology represents a promising approach to expanding solar PV generation capacity while addressing land use constraints and providing additional environmental benefits.

3.2.3.2 Ground-mounted bifacial PV systems

Bifacial PV systems are solar panels capable of capturing sunlight on both sides, distinguishing them from conventional monofacial solar panels that capture sunlight on only one side. This enables them to harness direct sunlight incident on the front side as well as the reflected sunlight reaching the rear side from the ground surface.

The front side of the bifacial module operates similarly to traditional monofacial modules, converting incident sunlight into electricity through the PV effect. However, the rear side captures additional sunlight reflected from the ground surface, increasing the overall energy yield of the system [22]. Even on surfaces like grass or soil, where sunlight reflects less, bifacial systems can still outperform monofacial systems. Other factors that affect the performance of bifacial PV are the tilt angle and the orientation relative to the sun's path. Choosing the proper tilt angle ensures that the panels capture the most sunlight throughout the year.

One key advantage of bifacial ground-mounted systems is their enhanced energy yield compared to their monofacial counterparts. Studies have shown that bifacial modules can achieve between 10% and 35% higher energy generation in certain conditions, particularly in locations with high albedo surfaces such as snow-covered ground or light-coloured pavement [22,23]. Bifacial PV systems also offer improved performance in diffuse lighting conditions, such as cloudy skies, due to their ability to capture reflected sunlight. This makes them particularly well-suited for regions with variable weather patterns or environments with limited direct sunlight exposure [22].

Overall, bifacial ground-mounted PV systems represent a technologically advanced solution for solar PV generation, offering increased efficiency, versatility, and durability in a wide range of environmental conditions.

For this work, **grass** has been chosen as the albedo.

3.2.3.3 BIPV

For buildings aiming to achieve near-zero energy standards, harnessing energy from the surrounding environment, particularly solar PV, is paramount. BIPV efficiently incorporates multifunctional elements into building facades and rooftops, offering aesthetic, economic and technical advantages.

BIPV can replace traditional building materials in rooftops and facades, transforming them into active components for energy production. This integration can be classified into different applications, including facades, rooftops, and other elements such as shading devices and balcony railings. Furthermore, advancements in BIPV technology, particularly in wall and window implementations, are crucial for driving future progress in the field [24].

For this work, the installation of BIPV on the **façade** has been considered. On facades, BIPV replaces traditional opaque or transparent elements, offering an innovative approach to energy-efficient building design. BIPV can be integrated into atrium covers, skylights, and shade structures, enhancing both the energy performance and architectural appeal of buildings [24].

While standardized prices for BIPV products may vary, the overall cost-effectiveness of BIPV compared to conventional construction materials is evident. Despite initial investment costs, BIPV systems offer long-term benefits in terms of energy savings, reduced environmental impact, and enhanced building value [24].

The efficiency and performance of BIPV systems may vary depending on factors such as material quality, building orientation, shading, and sunlight incidence. However, with proper design and installation, BIPV can provide a clean, economical and sustainable energy source while enhancing buildings' functionality and aesthetic appeal.

3.2.3.4 Ground-mounted monofacial PV systems

Monofacial ground-mounted PV systems are one of the most common configurations of solar PV installations. In this work, the monofacial system has been considered as a conventional alternative to identify the environmental performances of floating and bifacial systems. These systems consist of solar panels that capture sunlight only on one side, typically the front side. The panels are mounted on fixed structures or solar trackers that tilt them towards the sun to maximize the capture of direct sunlight.

Monofacial solar panels are manufactured with solar cells arranged in a single layer on the front side of the panel. Monofacial panels are generally more cost-effective and widely available compared to bifacial options. The efficiency and performance of ground-mounted monofacial systems depend on factors such as the quality of the panels, proper tilt and orientation, regular cleaning of the surfaces, and the amount of direct sunlight received. High-quality panels with advanced technology are crucial for better efficiency and durability. These systems are suitable for a wide range of applications, from residential and commercial installations to utility-scale energy projects [25].

Although monofacial ground-mounted systems capture only direct sunlight on the front side of the panels, they remain a popular and effective choice for solar PV generation, offering a cost-effective and reliable solution for transitioning to cleaner and more sustainable energy sources.

3.2.3.5 BAPV

In this work, the BAPV system has been considered a conventional alternative to identify the environmental actions of BIPV, but in this case, it has been considered that the system has been installed on the rooftop of the building. BAPV presents another avenue for integrating solar PV generation into building structures. BAPV systems are designed to be applied onto existing building surfaces rather than integrated directly into the construction materials. These systems offer flexibility in deployment and can be installed on various building elements such as roofs, facades, awnings, and canopies [26].

Advancements in BAPV technology are crucial for enhancing its efficiency and integration into building design. Innovations in mounting systems, panel materials, and installation techniques are driving progress in the field, making BAPV systems more accessible and attractive for building owners and developers.

Unlike BIPV, BAPV does not replace building components. Additionally, it can be mounted on a frame or as separate panels. It is opaque in nature and is only used to generate energy. It does not contribute to any heat gain inside the building but alleviates heat gain by shading the rooftop or wall.[26].

Overall, BAPV systems represent a promising solution for incorporating solar PV generation into existing buildings, offering a cost-effective and sustainable way to reduce reliance on traditional energy sources. As technology advances and awareness of environmental issues grows, BAPV is expected to play an increasingly important role in the transition to clean, renewable energy solutions.

3.2.4 Scenarios description

In the comprehensive environmental analysis of PV technologies, the importance of considering various scenarios to capture the complexities and dynamics in technological development and environmental conditions has been recognized.

In this sense, three key time horizons have been selected: 2022, 2030 and 2050. These horizons not only allow a long-term evaluation but also reflect some possible expected evolutions in PV technology, from current trends to future projections. The year 2022 represents the current state of the technology, serving as a starting point to compare the different technologies considered and their future improvements. On the other hand, the year 2030 has been considered an intermediate scenario, where technological innovations and advances in research are expected to drive improvements in the efficiency and profitability of PV systems. Finally, the year 2050 represents a long-term vision where technologies are anticipated to be more efficient, thus improving sustainability and mitigating climate change.

Each time horizon is associated with several key considerations. Firstly, the lifespan of the PV systems in each period has been analysed, recognizing the historical trend of increase in the durability and reliability of these systems. In addition, the efficiency of the PV system has been evaluated, taking into account both advances in the efficiency of solar cells and improvements in system design and engineering. Finally, the type of predominant solar cells in each period has been estimated, reflecting the expected trends in adopting specific technologies, from conventional to the most advanced and disruptive. These combined factors have enabled a holistic understanding of the evolution of PV technologies over time and will help better understand predictions of system penetration into the grid.

In addition**,** different scenarios covering various climatic zones have been explored. The analysis of these zones plays an essential role in the comprehensive evaluation of PV technologies. Environmental conditions, such as solar radiation, temperature, and precipitation, vary markedly by geographic location, which can significantly impact the performance and efficiency of PV systems. Therefore, a more complete understanding of the feasibility and effectiveness of PV technologies in various environmental contexts can be obtained by considering a wide range of climatic zones, from Mediterranean to subarctic climates.

In this context, three specific climatic zones have been selected: Subarctic, continental and Mediterranean, corresponding to Lappeenranta (Finland), Munich (Germany) and Murcia (Spain), respectively. These climate zones represent a diversity of environmental conditions that can significantly affect the performance and efficiency of PV systems. In climate scenarios, the main variation between zones has been determined by the annual average - global tilted irradiation, which varies depending on geographic location and local climatic conditions. This factor has a crucial influence on the performance and energy production of PV systems.

Murcia, located in Spain, has a Mediterranean climate characterized by high exposure to solar radiation. The Global Region of Incidence of Solar Radiation is high due to its relatively low latitude location, which promotes many sunny days with little cloud cover. In addition, the orientation towards the south in the northern hemisphere further enhances solar exposure in the region [27].

In contrast, Munich, Germany, exhibits a Continental climate. Although it is located further north than Murcia, it still receives significant solar radiation. However, the global region of incidence of solar radiation is lower than in Murcia due to the higher latitude, resulting in a lower solar incidence angle, along with atmospheric conditions that include higher cloud cover [28].

Finally, Lappeenranta in Finland is situated in a subarctic climate zone, where the global region of incidence of solar radiation is likely to be the lowest of the three locations due to its high latitude. This results in a shallow solar incidence angle, especially in winter when the sun is low on the horizon. Additionally, atmospheric conditions, such as cloud cover and snow, can further reduce the global region of incidence of solar radiation [29].

The detailed analysis of these scenarios has allowed us to identify the specific challenges and opportunities associated with each time horizon and climate zone and develop adapted strategies to maximize the performance and sustainability of PV systems.

3.2.5 Allocation rules

Modern systems often yield multiple useful products, necessitating the distribution of resource usage and environmental impacts among these products. Choosing an allocation method for multi-product systems is crucial and should align with the study's objectives and system boundaries. Various approaches exist for allocation methods, including system expansion, substitution, and partitioning (mass, energy, economic value, or other allocation rules) [14].

In the LCA analysis of PV technologies, the primary product obtained is electricity. Due to this singularity, there has not been a need to consider allocation rules to distribute resources or environmental impacts among multiple products.

3.2.6 Cut-off criteria

It is recommended that all processes and flows within the system under study be considered during an LCA. While not all may be quantitatively relevant, cut-off criteria can be applied to exclude certain inputs, outputs, life cycle stages, and processes or products. These criteria should be transparently documented and justified in the report, with considerations including mass, energy, and environmental importance. To establish cut-off criteria, the following procedure is recommended: include all process inputs and outputs, make conservative assumptions for missing data, prioritize inputs with potentially significant environmental impacts, and identify hazardous substances even if they fall below the cut-off threshold. Despite the complexity of LCA, simplifications through assumptions and limitations are often necessary for practicality.

It is important to note that while these simplifications may be necessary, it is essential to make them as accurate as possible to ensure that the LCA results are meaningful and reliable. Also, it is required to clearly communicate these assumptions and limitations to maintain transparency and allow for appropriate interpretation of the SERENDI-PV project findings. The assumptions and limitations established within the study are listed below:

- Different scenarios have been established considering 3 temporal horizons (2022, 2030, and 2050) and 3 climatic zones (Mediterranean, continental, and subarctic).
- All inventory data for simulating PV technologies have been obtained from reliable and relevant literature.
- Estimations have been made to consider the lifespan, efficiency, and performance of the systems, taking into account the different time horizons.
- For bifacial systems, grass has been considered as the albedo.
- An approximate distance of 500 km has been estimated to transport components to the installation site of the PV systems.
- An approximate distance of 500 km has been estimated to transport the waste at the end of the plant's lifespan to treatment points.
- For comparative analyses, systems have been categorized into utility-scale and small-scale systems.

These limitations and assumptions have been crucial for establishing the context and parameters of the LCA analysis of PV technologies.

3.3 Impact categories

The Life Cycle Impact Assessment (LCIA) phase aims to analyse the data collected during the LCI phase and calculate the potential environmental impacts associated with the inputs and outputs. To calculate the impacts, the LCIA method that has been chosen is the Environmental Footprint (EF) 3.1 method. In addition, the impact categories that have been selected to monitor the environmental performance of SERENDI-PV technologies are listed below (**Table 3.1**) [17]:

- **Acidification (AC):** This impact category is caused by pollutants like SO_2 and NOx reacting with moisture in the air to form acids. These acids then fall to the ground, negatively affecting soil, water bodies, as well as plants and animals. Emissions of NH_3, nitrogen oxides (NO, NO_2, NOx), and SO_2 contribute to environmental harm in this category.
- **Climate change, total (GW)**: This impact category represents the cumulative effect of additional radiative forcing over time (e.g., 20, 100, or 1000 years). GHG emissions, such as CO_2, CH_4, and N_2O, among others, are the primary drivers of this impact. Climate change has adverse effects on both

human health and the environment, including shifts in global average air temperatures, which can lead to significant ecological damage.

- **Particulate matter (PM):** This category accounts for the negative health impacts associated with particulate matter emissions and its precursors, such as NOx, SOx, and NH_3, which contribute to respiratory issues and other human health problems.
- **Eutrophication (EP):** Eutrophication occurs when excess nutrients from sources like sewage and fertilized farmland enter water bodies, promoting algae growth and other aquatic vegetation. The decay of this organic material depletes oxygen levels in the water, leading to oxygen deficiencies and, in severe cases, fish kills. This impact category measures the amount of oxygen required for the degradation of dead biomass. It includes three EP impact categories: Eutrophication – marine (MEP), Eutrophication – freshwater (FEP) and Eutrophication - terrestrial (TEP).
- **Human toxicity – cancer (HTc):** This category assesses the adverse health effects in humans caused by ingesting toxic substances through inhalation of air, ingestion of food/water, and penetration through the skin to the extent that they are related to cancer.
- **Human toxicity – non-cancer (HTnc):** Similar to HTc, this category evaluates the negative health impacts on humans due to exposure to toxic substances that do not cause cancer, excluding those related to particulate matter or ionizing radiation.
- **Ionizing irradiation (IR):** This category evaluates the potential health risks associated with exposure to ionizing radiation, including impacts on human health and the environment.
- **Land use (LU):** This impact category is related to the use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the amount of area involved and the duration of its occupation.
- **Ozone depletion (OD):** This impact category evaluates the depletion of the ozone layer in the Earth's stratosphere, primarily caused by emissions of ozone-depleting substances, such as chlorofluorocarbon (CFC), Halons, and hydrochlorofluorocarbon (HCFC), among others.
- **Photochemical ozone formation (POF):** This impact category assesses the formation of ground-level ozone due to chemical reactions between NOx and volatile organic compounds (VOCs) in the presence of sunlight.
- **Resource use, fossils (ADff):** This category is related to the use of non-renewable abiotic natural resources. ADff only includes the extraction of different fossil natural resources (e.g., natural gas, coal, oil).
- **Resource use, minerals, and metals (ADe)**: This category is related to the use of non-renewable abiotic natural resources. In the case of ADe, only the extraction of minerals and metals is considered.
- **Water use (WU):** Represents the amount of available water remaining per area in a watershed after the demand from humans and aquatic ecosystems is met. This impact category assesses the potential for water deprivation, whether for humans or ecosystems, based on the assumption that the less water available per area, the more likely it is that another user will be deprived.

Table 3.1: Impact categories in the EF 3.1

Impact category	Unidad	Abbreviation
Acidification	mol H+ eq	AC
Climate change	kg CO2 eq	GW
Particulate matter	disease inc.	PM
Eutrophication, marine	kg N eq	MEP
Eutrophication, freshwater	kg P eq	FEP
Eutrophication, terrestrial	mol N eq	TEP
Human toxicity, cancer	CTUh	HTc
Human toxicity, non-cancer	CTUh	HTnc
Ionizing irradiation	kBq U-235 eq	IR
Land use	Pt	LU
Ozone depletion	kg CFC11 eq	OD
Photochemical ozone formation	kg NMVOC eq	POF
Resource use, fossils	MJ	ADff
Resource use, minerals and metals	kg Sb eq	ADe
Water use	m3 depriv.	WU

4 LIFE CYCLE INVENTORY ANALYSIS

The LCI is a fundamental step of the LCA that provides a comprehensive and detailed inventory of inputs and outputs of a product or service throughout its life cycle. It involves identifying and quantifying all the materials, energy, and emissions associated with the various stages of a product's life, from raw material extraction, production, distribution, use, and disposal or recycling.

In this phase, the collection of data (inputs and outputs) related to the product, process or service must be completed. **Table 4.1** shows an example of the types of inputs and outputs of a process.

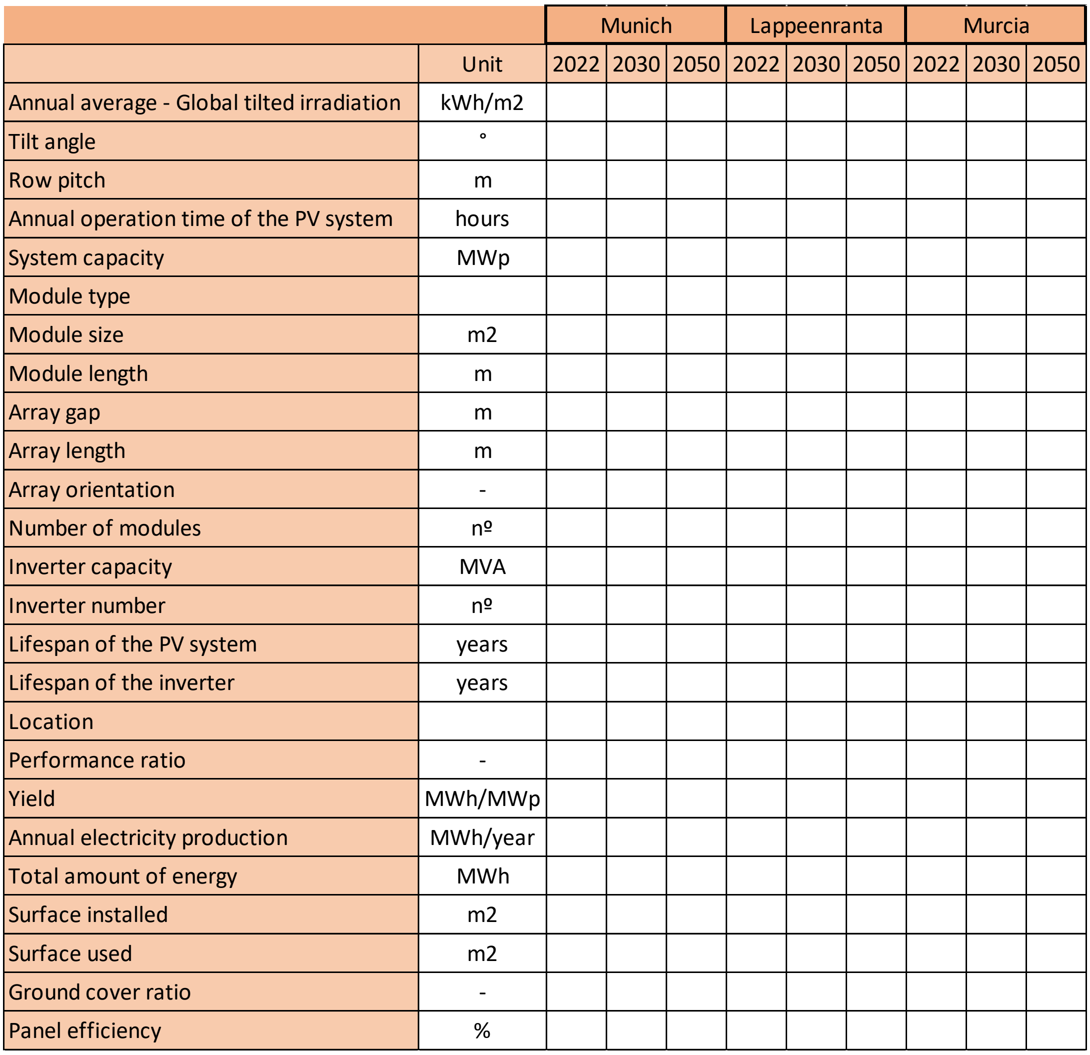
Table 4.1: Process inputs and outputs necessary to calculate the environmental impacts

INPUTS	OUTPUTS
Energy consumption: all inputs related to energy (electricity, natural gas, etc.).	Emissions to air: all substances released into the atmosphere.
Raw materials: materials present in the product composition.	Emissions to water: all substances that are released to water streams.
Auxiliary materials: materials needed to manufacture the product.	Emissions to soil: all substances filtered into the soil.
Water consumption: all inputs related to water.	Waste: material flows to treatment.
Transport: transport needed for all materials and waste.	Products: final product or intermediate product.

Data directly acquired from the process being studied is recommended whenever possible. This can be achieved through various means such as on-site measurements, material and energy balances, interviews with stakeholders along the production chain or established databases. However, challenges may arise during the collection of inventory data, leading to the identification of issues with the initially defined conditions. In such cases, it may be necessary to reconsider the data requirements or limitations or even adjust the system boundaries or data collection procedures to align with the study objectives.

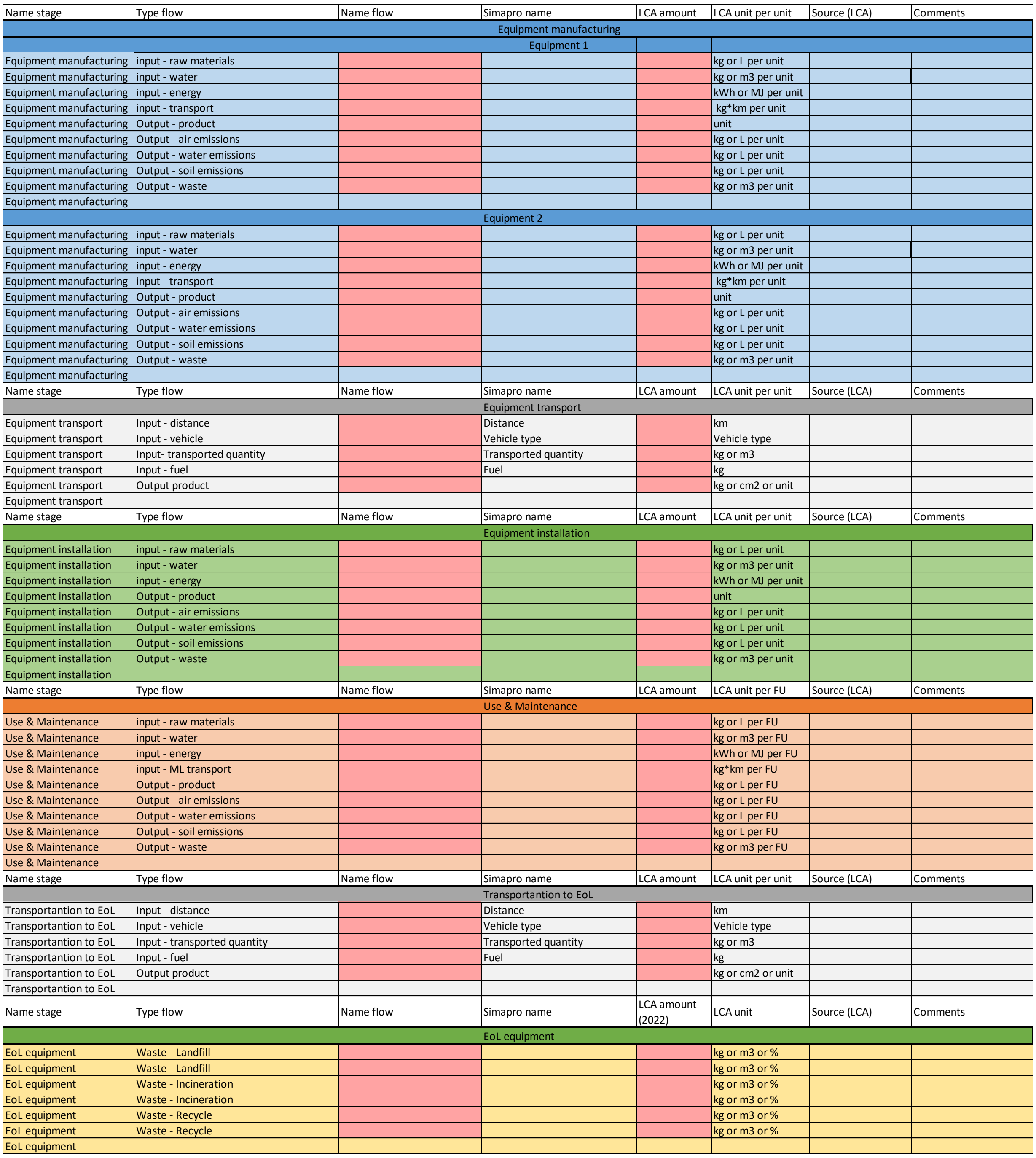
However, since the project's goal is to develop technologies for monitoring and optimizing PV systems, rather than developing or manufacturing the systems themselves, inventory data related to the production, installation, operation, and dismantling of the systems could not be collected directly from the project partners. Consequently, this inventory data has been sourced from relevant literature and databases.

To facilitate the calculation of inventory data, supplementary data have been collected to consolidate the general information of the process (**Figure 4.1**). Moreover, for the SERENDI-PV project, an Excel spreadsheet has been developed to compile the LCI data encompassing all inputs and outputs for all the stages included in the cradle-to-grave approach (**Figure 4.2**).



		Munich			Lappeenranta			Murcia		
	Unit	2022	2030	2050	2022	2030	2050	2022	2030	2050
Annual average - Global tilted irradiation	kWh/m2									
Tilt angle	°									
Row pitch	m									
Annual operation time of the PV system	hours									
System capacity	MWp									
Module type										
Module size	m2									
Module length	m									
Array gap	m									
Array length	m									
Array orientation	-									
Number of modules	nº									
Inverter capacity	MVA									
Inverter number	nº									
Lifespan of the PV system	years									
Lifespan of the inverter	years									
Location										
Performance ratio	-									
Yield	MWh/MWp									
Annual electricity production	MWh/year									
Total amount of energy	MWh									
Surface installed	m2									
Surface used	m2									
Ground cover ratio	-									
Panel efficiency	%									

Figure 4.1: General data as part of the LCI template



Name stage	Type flow	Name flow	Simapro name	LCA amount	LCA unit per unit	Source (LCA)	Comments
Equipment manufacturing							
Equipment 1							
Equipment manufacturing	input - raw materials				kg or L per unit		
Equipment manufacturing	input - water				kg or m3 per unit		
Equipment manufacturing	input - energy				kWh or MJ per unit		
Equipment manufacturing	input - transport				kg*km per unit		
Equipment manufacturing	Output - product				unit		
Equipment manufacturing	Output - air emissions				kg or L per unit		
Equipment manufacturing	Output - water emissions				kg or L per unit		
Equipment manufacturing	Output - soil emissions				kg or L per unit		
Equipment manufacturing	Output - waste				kg or m3 per unit		
Equipment manufacturing							
Equipment 2							
Equipment manufacturing	input - raw materials				kg or L per unit		
Equipment manufacturing	input - water				kg or m3 per unit		
Equipment manufacturing	input - energy				kWh or MJ per unit		
Equipment manufacturing	input - transport				kg*km per unit		
Equipment manufacturing	Output - product				unit		
Equipment manufacturing	Output - air emissions				kg or L per unit		
Equipment manufacturing	Output - water emissions				kg or L per unit		
Equipment manufacturing	Output - soil emissions				kg or L per unit		
Equipment manufacturing	Output - waste				kg or m3 per unit		
Equipment manufacturing							
Name stage	Type flow	Name flow	Simapro name	LCA amount	LCA unit per unit	Source (LCA)	Comments
Equipment transport							
Equipment transport	Input - distance		Distance		km		
Equipment transport	Input - vehicle		Vehicle type		Vehicle type		
Equipment transport	Input- transported quantity		Transported quantity		kg or m3		
Equipment transport	Input - fuel		Fuel		kg		
Equipment transport	Output product				kg or cm2 or unit		
Equipment transport							
Name stage	Type flow	Name flow	Simapro name	LCA amount	LCA unit per unit	Source (LCA)	Comments
Equipment installation							
Equipment installation	input - raw materials				kg or L per unit		
Equipment installation	input - water				kg or m3 per unit		
Equipment installation	input - energy				kWh or MJ per unit		
Equipment installation	Output - product				unit		
Equipment installation	Output - air emissions				kg or L per unit		
Equipment installation	Output - water emissions				kg or L per unit		
Equipment installation	Output - soil emissions				kg or L per unit		
Equipment installation	Output - waste				kg or m3 per unit		
Equipment installation							
Name stage	Type flow	Name flow	Simapro name	LCA amount	LCA unit per FU	Source (LCA)	Comments
Use & Maintenance							
Use & Maintenance	input - raw materials				kg or L per FU		
Use & Maintenance	input - water				kg or m3 per FU		
Use & Maintenance	input - energy				kWh or MJ per FU		
Use & Maintenance	input - ML transport				kg*km per FU		
Use & Maintenance	Output - product				kg or L per FU		
Use & Maintenance	Output - air emissions				kg or L per FU		
Use & Maintenance	Output - water emissions				kg or L per FU		
Use & Maintenance	Output - soil emissions				kg or L per FU		
Use & Maintenance	Output - waste				kg or m3 per FU		
Use & Maintenance							
Name stage	Type flow	Name flow	Simapro name	LCA amount	LCA unit per unit	Source (LCA)	Comments
Transportantion to EoL							
Transportantion to EoL	Input - distance		Distance		km		
Transportantion to EoL	Input - vehicle		Vehicle type		Vehicle type		
Transportantion to EoL	Input - transported quantity		Transported quantity		kg or m3		
Transportantion to EoL	Input - fuel		Fuel		kg		
Transportantion to EoL	Output product				kg or cm2 or unit		
Transportantion to EoL							
Name stage	Type flow	Name flow	Simapro name	LCA amount (2022)	LCA unit	Source (LCA)	Comments
EoL equipment							
EoL equipment	Waste - Landfill				kg or m3 or %		
EoL equipment	Waste - Landfill				kg or m3 or %		
EoL equipment	Waste - Incineration				kg or m3 or %		
EoL equipment	Waste - Incineration				kg or m3 or %		
EoL equipment	Waste - Recycle				kg or m3 or %		
EoL equipment	Waste - Recycle				kg or m3 or %		
EoL equipment							

Figure 4.2: LCI template to collect the inventory data for PV systems

Collecting a wide range of data related to different aspects of these systems (equipment manufacturing, transportation, installation, use and maintenance and end-of-life (EoL)) has been essential to perform a detailed LCA of PV systems and understanding their environmental impact. These data have been used to calculate the inventories associated with the FU, which, in this case, has been the production of 1 kWh of electricity. Information related to several key parameters that directly affect the performance and efficiency of PV systems has been collected to calculate the LCI.

One of the most critical parameters has been the annual average inclined global irradiation, which represents the amount of solar radiation incident on an inclined surface. This data has been essential to calculate the energy production of a PV system in a specific location. Another relevant parameter has been the inclination angle, which determines the optimal inclination of the solar panels to maximize the capture of solar radiation.

The annual operating time of the PV system and the system capacity has been crucial to calculate the total amount of energy produced by the system throughout the year. The choice of the type of module, its size, and the space between modules have also been determining factors in the system's performance and efficiency.

In addition, aspects related to the supporting infrastructure must be considered, such as the inverter's capacity, the number of inverters, and the useful life of both the PV system and the inverter. These elements significantly impact the system's operation and maintenance throughout its useful life.

Other essential data includes performance, energy efficiency, annual electricity production, the total amount of energy generated, installed area and utilized area of the system, as well as land coverage index and panel efficiency. This data has provided detailed information on the performance and efficiency of the system under actual operating conditions.

The collection of this wide range of data has been essential to perform a comprehensive LCA of PV systems and understand their environmental impact in different geographical and temporal contexts. This information is summarized in the **Table** 4.2**, Table 4.3, Table 4.4, Table 4.5** and **Table 4.6**.

Table 4.2: General information for Floating system

Key parameter		Munich			Lappeenranta			Murcia		
	Unit	2022	2030	2050	2022	2030	2050	2022	2030	2050
Annual average - Global tilted irradiation	kWh/m^2	1,048			1,327			1,978		
Tilt	°	15								
Annual operation time	hours/year	1,500			1,780			2,970		
System capacity	MWp	20								
Module type		mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks
Module size	m^2	2.58								
Number of modules	nº	36,394	32,571	25,840	36,394	32,571	25,840	36,394	32,571	25,840
Inverter capacity	MVA	2.20								
Inverter number	nº	9								
Lifespan of the PV system	years	30	40	40	30	40	40	30	40	40
Lifespan of the inverter	years	20								
Performance Ratio (PR)	%	90.6			91.9			90.1		
Yield	MWh/MWp	950			1,234			1,826		
Annual electricity generation	MWh/year	18,995			24,686			36,525		
Total amount of electricity	MWh	569,855	759,804	759,814	740,574	987,428	987,441	1,095,760	1,461,009	1,461,028
Surface installed	m^2	93,897	84,033	66,667	93,897	84,033	66,667	93,897	84,033	66,667
Surface used	m^2	149,570	133,858	106,196	149,570	133,858	106,196	149,570	133,858	106,196
Panel efficiency	%	21.3	23.8	30.0	21.3	23.8	30.0	21.3	23.8	30.0

Table 4.3: General information for Bifacial system

Key parameter		Lappeenranta			Munich			Murcia		
	Unit	2022	2030	2050	2022	2030	2050	2022	2030	2050
Annual average - Global tilted irradiation	kWh/m^2	1,142			1,395			2,050		
Tilt	°	40			31			26		
Annual operation time	hours/year	1,500			1,780			2,970		
System capacity	MWp	50								
Module type		mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks
Module size	m^2	2.58								
Number of modules	nº	90,985	81,428	64,599	90,985	81,428	64,599	90,985	81,428	64,599
Inverter capacity	MVA	2.20								
Inverter number	nº	21								
Lifespan of the PV system	years	30	40	40	30	40	40	30	40	40
Lifespan of the inverter	years	20								
Performance ratio (PR)	%	94.9			97.5			94.3		
Yield	MWh/MWp	1,142	1,151	1,151	1,452	1,465	1,465	2,076	2,097	2,097
Annual electricity generation	MWh/year	57,120	57,536	57,536	72,588	73,243	73,243	103,817	104,843	104,842
Total amount of electricity	MWh	1,713,593	2,301,443	2,301,423	2,177,632	2,929,727	2,929,702	3,114,501	4,193,727	4,193,691
Surface installed	m^2	234,741	210,084	166,665	234,741	210,084	166,665	234,741	210,084	166,665
Surface used	m^2	647,562	579,543	459,767	593,599	531,248	421,453	485,672	434,657	344,825
Frontside efficiency	%	21.3	23.8	30.0	21.3	23.8	30.0	21.3	23.8	30.0
Bifacial gains (albedo=grass)	%	5.37	6.14	6.14	6.74	7.71	7.71	7.43	8.50	8.50

Table 4.4: General information for Monofacial system

Key parameter		Lappeenranta			Munich			Murcia		
	Unit	2022	2030	2050	2022	2030	2050	2022	2030	2050
Annual average - Global tilted irradiation	kWh/m^2	1,142			1,395			2,050		
Tilt	°	40			31			26		
Annual operation time	hours/year	1,500			1,780			2,970		
System capacity	MWp	50								
Module type		mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks
Module size	m^2	2.58								
Number of modules	nº	90,985	81,428	64,599	90,985	81,428	64,599	90,985	81,428	64,599
Inverter capacity	MVA	2.20								
Inverter number	nº	21								
Lifespan of the PV system	years	30	40	40	30	40	40	30	40	40
Lifespan of the inverter	years	20								
Performance ratio (PR)	%	89.4			91.2			87.4		
Yield	MWh/MWp	1,021			1,273			1,791		
Annual electricity generation	MWh/year	51,042			63,628			89,532		
Total amount of electricity	MWh	1,531,270	2,041,699	2,041,682	1,908,847	2,545,137	2,545,116	2,685,967	3,581,300	3,581,270
Surface installed	m^2	234,741	210,084	166,665	234,741	210,084	166,665	234,741	210,084	166,665
Surface used	m^2	647,562	579,543	459,767	593,599	531,248	421,453	485,672	434,657	344,825
Frontside efficiency	%	21.3	23.8	30.0	21.3	23.8	30.0	21.3	23.8	30.0

Table 4.5: General information for BIPV system

Key parameter		Lappeenranta			Munich			Murcia		
	Unit	2022	2030	2050	2022	2030	2050	2022	2030	2050
Annual average - Global tilted irradiation	kWh/m^2	860			964			1,326		
Tilt	°	90								
Annual operation time	hours/year	1,500			1,780			2,970		
System capacity	MWp	0,0423								
Module type		mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks
Module size	m^2	1.95								
Number of modules	nº	126	111	88	126	111	88	126	111	88
Inverter capacity	MVA	0.01								
Inverter number	nº	5								
Lifespan of the PV system	years	40	40	50	40	40	50	40	40	50
Lifespan of the inverter	years	20								
Performance ratio (PR)	%	75	77	80	75	77	80	75	77	80
Yield	MWh/MWp	663	688	997	725	743	771	997	1,022	1,061
Annual electricity generation	MWh/year	30	31	32	34	34	36	46	47	49
Total amount of electricity	MWh	1,198	1,228	1,594	1,342	1,376	1,786	1,847	1,893	2,457
Surface installed	m^2	246	216	172	246	216	172	246	216	172
Frontside efficiency	%	18.9	21.4	27.0	18.9	21.4	27.0	18.9	21.4	27.0

Table 4.6: General information for BAPV system

Key parameter		Lappeenranta			Munich			Murcia		
	Unit	2022	2030	2050	2022	2030	2050	2022	2030	2050
Annual avarage - Global tilted irradiation	kWh/m^2	1,134			1,405			2,062		
Tilt	°	35								
Annual operation time	hours/year	1,500			1,780			2,970		
System capacity	MWp	0,0079								
Module type		mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks	mc-type PERC	mc n-type TOPCON	Tandem pks
Module size	m^2	1.95								
Number of modules	nº	19	17	14	19	17	14	19	17	14
Inverter capacity	MVA	0.01								
Inverter number	nº	1								
Lifespan of the PV system	years	40	40	50	40	40	50	40	40	50
Lifespan of the inverter	years	20								
Performance ratio (PR)	%	89.4			91.2			87.4		
Yield	MWh/MWp	840	840	872	1,037	1,037	1,076	1,475	1,475	1,531
Annual electricity generation	MWh/year	6.64	6.64	6.89	8.19	8.19	8.50	11.66	11.65	12.10
Total amount of electricity	MWh	199	265	276	246	328	340	350	466	484
Surface installed	m^2	37.1	33.2	27.3	37.1	33.2	27.3	37.1	33.2	27.2
Frontside efficiency	%	21.3	23.8	30.0	21.3	23.8	30.0	21.3	23.8	30.0

Once the general information about the PV system was collected, an exhaustive literature search has been carried out to collect inventory data for each part of the PV system. In this sense, **Table 4.7, Table 4.8** and **Table 4.9** present the inventory for the monocrystalline PERC-type cells, monocrystalline (Mc) n-type TOPCON and perovskite, respectively. These data correspond to manufacturing 1m^2 of cells, used as a reference unit. It is important to note that these cells have been considered for each time horizon of 2022, 2030 and 2050, respectively, and that the cells have been used in all five PV systems considered.

Table 4.7: Inventory data for the Cell manufacturing: Monocrystalline-type PERC [30]

Environmental aspect	Value	Unit	LCI dataset
Cell manufacturing (monocrystalline-type PERC) (per m^2) – 2022			
Wafer	1.00E+00	m^2	market for single-Si wafer, PV (GLO)
Oxygen, liquid	1.71E-03	kg	market for oxygen, liquid (RER)
Phosphoryl chloride	6.15E-04	kg	market for phosphorous chloride (RER)
Compressed air	4.50E-01	m^3	market for compressed air, 600 kPa gauge (RER)
Water	2.95E+01	kg	market for water, deionised (Europe without Switzerland)
Hydrochloric acid	9.98E-03	kg	market for hydrochloric acid, without water, in 30% solution state (RER)
Additive	1.16E-02	kg	market for chemical, organic (GLO)
Hydrogen fluoride	3.83E-02	kg	market for hydrogen fluoride (RER)
Potassium hydroxide	1.14E-01	kg	market for potassium hydroxide (GLO)
Hydrogen peroxide	8.21E-02	kg	market for hydrogen peroxide, without water, in 50% solution state (RER)
Nitric acid	5.40E-02	kg	market for nitric acid, without water, in 50% solution state (RER)
Argon	6.86E-04	kg	market for argon, liquid (RER)
Silane	2.93E-03	kg	market for silicon tetrahydride (GLO)
Ammonia	3.17E-03	kg	market for ammonia, anhydrous, liquid (RER)
Nitrous oxide	1.38E-03	kg	market for nitrous oxide (GLO)
Tetramethylammonium iodide	1.77E-04	kg	market for chemical, organic (GLO)
Metallization paste	1.14E-01	kg	market for metallization paste, back side (RER)
Metallization paste	3.75E-03	kg	market for metallization paste, front side (RER)
Butyldiglycol	4.69E-02	kg	market for butyldiglycol acetate (GLO)
PV cell factory	4.00E-07	p	market for PV cell factory (GLO)
Electricity	1.24E+01	kWh	market for electricity, medium voltage (Europe without Switzerland)
Waste solvents	-1.57E-01	kg	market for spent solvent mixture (Europe without Switzerland)
Waste landfill	-2.01E+00	kg	market for waste, from silicon wafer production (GLO)
Wastewater	-1.45E-01	m^3	market for wastewater from PV cell production (RoW)

Table 4.8: Inventory data for the Cell manufacturing: Monocrystaline n-type TOPCON

Environmental aspect	Value	Unit	LCI dataset
			Cell manufacturing (mc n-type TOPCON) (per m^2) – 2030
Water	9.40E+02	kg	market for water, deionised (Europe without Switzerland)
Hydrogen fluoride	9.50E-02	kg	market for hydrogen fluoride (RER)
Sodium hydroxide	1.56E-01	kg	market for sodium hydroxide, without water, in 50% solution state (RER)
Hydrogen peroxide	5.60E-02	kg	market for hydrogen peroxide, without water, in 50% solution state (RER)
Hydrochloric acid	6.10E-02	kg	market for hydrochloric acid, without water, in 30% solution state (RER)
Ammonia	1.00E-02	kg	market for ammonia, anhydrous, liquid (RER)
Compressed air	1.63E-00	m^3	market for compressed air, 600 kPa gauge (RER)
Silane	1.62E-03	kg	market for silicon tetrahydride (GLO)
Hydrogen (gaseous)	2.42E-03	kg	market for hydrogen, gaseous (GLO
Oxygen, liquid	5.36E-03	kg	market for oxygen, liquid (RER)
Indium tin oxide powder	2.74E-03	kg	market for indium tin oxide powder, nanoscale, for sputtering target (RER)
Metallization paste	2.96E-02	kg	market for metallization paste, back side (RER)
Metallization paste	2.96E-02	kg	market for metallization paste, front side (RER)
Nitrogen	4.30E-03	kg	market for nitrogen, liquid (RER)
Propane	3.30E-03	kg	market for propane (GLO)
Electricity (medium voltage)	1.45E+01	kWh	market for electricity, medium voltage (Europe without Switzerland)
PV cell factory	4.00E-07	p	market for PV cell factory (GLO)
Wastewater	-3.35E-02	m^3	market for wastewater from PV cell production (RoW)

Table 4.9: Inventory data for the Cell manufacturing: Perovskite/c-Si tandem [31]

Environmental aspect	Value	Unit	LCI dataset
			Cell manufacturing (Perovskite/c-Si tandem) (per m^2) – 2050
Lithium fluoride	1.76E-03	kg	market for lithium fluoride (GLO)
Argon	1.16E-01	kg	market for argon, crude, liquid (GLO)
Indium tin oxide powder	4.77E-06	kg	market for indium tin oxide powder, nanoscale, for sputtering target (RER)
Tin dioxide	1.39E-04	kg	market for tin dioxide (GLO)
Oxygen	1.16E-02	kg	market for oxygen, liquid (RER)
Nitrogen	4.41E+00	kg	market for nitrogen, liquid (RER)
Phosphoric acid	1.13E-06	kg	market for phosphoric acid, industrial grade, without water, in 85% solution state (GLO)
Ethanol	1.20E-03	kg	market for ethanol, without water, in 99.7% solution state, from fermentation (RER)
Silver	2.10E-03	kg	market for silver (GLO)

Environmental aspect	Value	Unit	LCI dataset
Iodine	1.14E-03	kg	market for iodine (GLO)
Hydrogen sulfide	1.60E-05	kg	market for hydrogen sulfide (RER)
Methylamine	6.61E-05	kg	market for methylamine (RER)
Diethyl ether	2.37E-03	kg	market for diethyl ether, without water, in 99.95% solution state (RER)
Acetic acid	2.42E-04	kg	market for acetic acid, without water, in 98% solution state (GLO)
Ammonia	2.82E-01	kg	market for ammonia, anhydrous, liquid (RER)
Hydrochloric acid	6.76E-02	kg	market for hydrochloric acid, without water, in 30% solution state (RER)
Hydrogen cyanide	7.68E-05	kg	market for hydrogen cyanide (RER)
Steam	3.23E-03	kg	market for steam, in chemical industry (RER)
Solvent	1.86E-03	kg	market for solvent, organic (GLO)
Hydrazine	7.71E-13	kg	market for hydrazine (RER)
Potassium hydroxide	4.42E-04	kg	market for potassium hydroxide (GLO)
Lead	6.82E-04	kg	market for lead (GLO)
Nitric acid	1.11E-03	kg	market for nitric acid, without water, in 50% solution state (RER)
Lithium carbonate	2.33E-05	kg	market for lithium carbonate (GLO)
Bromine	1.23E-05	kg	market for bromine (GLO)
Hydrogen (gaseous)	4.59E-03	kg	market for hydrogen, gaseous (GLO
Deionised water	3.34E+01	kg	market for water, deionised (Europe without Switzerland)
Dimethyl sulfoxide	5.00E-03	kg	market for dimethyl sulfoxide (GLO)
Toluene	1.35E-02	kg	market for toluene, liquid (RER)
N,N-dimethylformamide	2.09E-03	kg	market for N,N-dimethylformamide (GLO)
Isopropanol	5.16E-03	kg	market for isopropanol (RER)
Cyclohexane	2.92E-02	kg	market for cyclohexane (GLO)
Sodium hypochlorite	1.18E-02	kg	market for sodium hypochlorite, without water, in 15% solution state (RER)
Indium tin oxide	2.00E-08	kg	market for sputtering, indium tin oxide, for liquid crystal display (GLO)
Silicon tetrahydride	1.72E-04	kg	market for silicon tetrahydride (GLO)
Phosphane	2.30E-07	kg	market for phosphane (GLO)
Carbon dioxide	8.06E-06	kg	market for carbon dioxide, liquid (RER)
Fluorine	6.93E-03	kg	market for fluorine, liquid (RER)
hydrogen (liquid)	2.40E-04	kg	market for hydrogen, liquid (RER)
Hydrogen fluoride	1.00E-01	kg	market for hydrogen fluoride (RER)
Sodium hydroxide	1.60E-01	kg	market for sodium hydroxide, without water, in 50% solution state (RER)
Hydrogen peroxide	6.00E-02	kg	market for hydrogen peroxide, without water, in 50% solution state (RER)
Compressed air	2.64E-01	m^3	market for compressed air, 1200 kPa gauge (RER)

Environmental aspect	Value	Unit	LCI dataset
Wafer	1.00E+00	m^2	market for single-Si wafer, PV (GLO)
Aluminium	5.67E-05	kg	market for aluminium, wrought alloy (GLO)
Propane	3.30E+00	kg	market for propane (GLO)
Heat	7.16E-03	MJ	market for heat, from steam, in chemical industry (RER)
Electricity (medium voltage)	5.94E+01	kWh	market for electricity, medium voltage (Europe without Switzerland)
Electricity (low voltage)	3.57E+00	kWh	market for electricity, low voltage (Europe without Switzerland)
PV cell factory	4.00E-07	p	market for PV cell factory (GLO)
Waste solvents	-3.41E-03	kg	market for spent solvent mixture (Europe without Switzerland)
Waste incineration	-7.87E-04	kg	market for hazardous waste, for incineration (Europe without Switzerland)

The other components of the system, such as panel manufacturing, electrical elements, mounting system and inverters, have been assumed to have uniform manufacturing throughout the three-time horizons. Likewise, it is important to highlight that some components may share the same inventory between different systems. For example, in terms of panel manufacturing, the same panel type can be used for floating, monofacial and BAPV systems (**Table 4.10**). In the case of BIPV, there has been a slight variation since the aluminium structure is not required (**Table 4.12**). Finally, the bifacial panels are completely different and require a specific approach in their manufacturing process **(Table 4.11**). Another component that exhibits similarities across various systems is the PV mounting system, which has been estimated to be similar for both bifacial and monofacial systems (**Table 4.13**). Conversely, in the other systems, this component differs significantly in each of them (**Table 4.14**, **Table 4.15** and **Table** 4.16). In the realm of electrical and electronic components, a clear division has emerged. For utility-scale systems (1.3 MWp) (**Table 4.17**), a single type of electronic component is utilized, whereas smaller systems have been divided into two distinct categories: one of 93 kWp for BIPV (**Table 4.18**) and another of 3 kWp for BAPV (**Table 4.19**). Regarding inverters, also a clear division has emerged. Larger systems utilize the same type of inverters (**Table 4.20**) as smaller systems (**Table 4.21**). On the other hand, inventory data associated with the EoL stages of each component have also been added to these tables.

Table 4.10: Inventory data for the panel manufacturing and EoL stages (floating, monofacial and BAPV systems) [32]

Environmental aspect	Value	Unit	LCI dataset
Panel manufacturing stage (floating, monofacial and BAPV) (per m^2) – 2022, 2030 and 2050			
1-propanol	8.14E-03	kg	market for 1-propanol (GLO)
Acetone	1.30E-02	kg	market for acetone, liquid (RER)
Aluminium alloy	2.63E+00	kg	market for aluminium alloy, AlMg3 (GLO)
Brazing solder	8.78E-03	kg	market for brazing solder, cadmium free (GLO)
Copper	1.13E-01	kg	market for copper, cathode (GLO)
Ethylvinylacetate	1.00E+00	kg	market for ethylvinylacetate, foil (GLO)
Glass fibre reinforced plastic	1.88E-01	kg	market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)
Lubricating oil	1.61E-03	kg	market for lubricating oil (RER)
Methanol	2.16E-03	kg	market for methanol (GLO)

Environmental aspect	Value	Unit	LCI dataset
Nickel, class 1	1.63E-04	kg	market for nickel, class 1 (GLO)
Cell	9.32E-01	m^2	Simulated
Panel factory	4.00E-06	p	market for PV panel factory (GLO)
Polyethylene terephthalate	3.73E-01	kg	market for polyethylene terephthalate, granulate, amorphous (GLO)
Polyvinylfluoride, film	1.10E-01	kg	market for polyvinylfluoride, film (GLO)
Silicone product	1.22E-01	kg	market for silicone product (GLO)
Solar glass	1.01E+01	kg	market for solar glass, low-iron (GLO)
Tap water	2.13E+01	kg	market for tap water (RER)
Tempering	1.01E+01	kg	market for tempering, flat glass (RER)
Vinyl acetate	1.64E-03	kg	market for vinyl acetate (GLO)
Wire drawing	1.13E-01	kg	market for wire drawing, copper (GLO)
Electricity	4.71E+00	kWh	market for electricity, medium voltage (Europe without Switzerland)
Heat	4.87E+00	MJ	market for heat, district or industrial, natural gas (Europe without Switzerland)
Municipal solid waste	-3.00E-02	kg	market for municipal solid waste (RER)
Waste mineral oil	-1.61E-03	kg	market for waste mineral oil (Europe without Switzerland)
Waste plastic	-1.19E+00	kg	market for waste plastic, mixture (RER)
Waste polyvinylfluoride	-1.10E-01	kg	market for waste polyvinylfluoride (CH)
Wastewater	-2.10E-02	kg	market for wastewater, average (Europe without Switzerland)
Panel EoL stage (floating, monofacial and BAPV) (per m^2) – 2022, 2030 and 2050			
Glass (waste)	2.02E+00	kg	market group for waste glass (Europe without Switzerland)
Glass (recycle)	8.08E+00	kg	waste packaging glass, unsorted, Recycled Content cut-off (GLO)
Aluminium (waste)	2.63E-01	kg	market for scrap aluminium (Europe without Switzerland)
Aluminium (recycle)	2.37E+00	kg	recycling of aluminium (GLO)
Copper (waste)	1.13E-01	kg	market for scrap copper (Europe without Switzerland)
Plastic (recycle)	1.56E-01	kg	market group for waste plastic, mixture (Europe without Switzerland)
Other waste	4.14E+00	kg	market for hazardous waste, for incineration (Europe without Switzerland)

Table 4.11: Inventory data for the panel manufacturing and EoL stages (bifacial systems) [30]

Environmental aspect	Value	Unit	LCI dataset
Panel manufacturing stage (bifacial) (per m^2) – 2022, 2030 and 2050			
Flat glass	4.84E+01	kg	market for flat glass, uncoated (RER)
Tempering	4.84E+01	kg	market for tempering, flat glass (GLO)
Ethylvinylacetate	9.80E-01	kg	market for ethylvinylacetate, foil (GLO)
Tin	5.99E-02	kg	market for tin (GLO)
Lead	5.99E-02	kg	market for lead (GLO)
Wire drawing	2.10E-01	kg	market for wire drawing, copper (GLO)
Flux (wave soldering)	2.00E-03	kg	market for flux, for wave soldering (GLO)
Polyethylene terephthalate	1.90E-02	kg	market for polyethylene terephthalate, granulate, amorphous (GLO)
Extrusion (plastic)	1.90E-02	kg	market for extrusion, plastic film (RER)
Silicone product	1.00E-03	kg	market for silicone product (GLO)
Glass fibre reinforced plastic	1.50E-01	kg	market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)
Wire drawing	1.50E-01	kg	market for wire drawing, copper (GLO)
Copper	1.50E-01	kg	market for copper, cathode (GLO)
Silicone product	3.00E-02	kg	market for silicone product (GLO)
Tap water	2.13E+01	kg	market for tap water (RER)
Electricity	1.02E+01	kWh	market for electricity, medium voltage (Europe without Switzerland)
Panel factory	4.00E-06	p	market for PV panel factory (GLO)
Cell	9.32E-01	m^2	Simulated
Municipal solid waste	-3.00E-02	kg	market for municipal solid waste (RER)
Waste plastic	-1.19E+00	kg	market for waste plastic, mixture (RER)
Wastewater	-2.10E-02	kg	market for wastewater, average (Europe without Switzerland)
Panel EoL stage (bifacial) (per m^2) – 2022, 2030 and 2050			
Glass (waste)	4.84E+00	kg	market group for waste glass (Europe without Switzerland)
Glass (recycle)	1.94E+01	kg	waste packaging glass, unsorted, Recycled Content cut-off (GLO)
Copper (waste)	1.50E-01	kg	market for scrap copper (Europe without Switzerland)
PVA (recycle)	9.80E-01	kg	recycling of PVC (GLO)
Plastic (recycle)	1.90E-02	kg	market group for waste plastic, mixture (Europe without Switzerland)
Other waste	5.15E+00	kg	market for hazardous waste, for incineration (Europe without Switzerland)

Table 4.12: Inventory data for the panel manufacturing and EoL stages (BIPV systems) [32]

Environmental aspect	Value	Unit	LCI dataset
Panel manufacturing stage (BIPV) (per m^2) – 2022, 2030 and 2050			
1-propanol	8.14E-03	kg	market for 1-propanol (GLO)
Acetone	1.30E-02	kg	market for acetone, liquid (RER)
Brazing solder	8.78E-03	kg	market for brazing solder, cadmium free (GLO)
Copper	1.13E-01	kg	market for copper, cathode (GLO)
Ethylvinylacetate	1.00E+00	kg	market for ethylvinylacetate, foil (GLO)
Glass fibre reinforced plastic	1.88E-01	kg	market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)
Lubricating oil	1.61E-03	kg	market for lubricating oil (RER)
Methanol	2.16E-03	kg	market for methanol (GLO)
Nickel, class 1	1.63E-04	kg	market for nickel, class 1 (GLO)
Cell	9.32E-01	m^2	Simulated
Panel factory	4.00E-06	p	market for PV panel factory (GLO)
Polyethylene terephthalate	3.73E-01	kg	market for polyethylene terephthalate, granulate, amorphous (GLO)
Polyvinylfluoride, film	1.10E-01	kg	market for polyvinylfluoride, film (GLO)
Silicone product	1.22E-01	kg	market for silicone product (GLO)
Solar glass	1.01E+01	kg	market for solar glass, low-iron (GLO)
Tap water	2.13E+01	kg	market for tap water (RER)
Tempering	1.01E+01	kg	market for tempering, flat glass (RER)
Vinyl acetate	1.64E-03	kg	market for vinyl acetate (GLO)
Wire drawing	1.13E-01	kg	market for wire drawing, copper (RER)
Electricity	4.71E+00	kWh	market for electricity, medium voltage (Europe without Switzerland)
Heat	4.87E+00	MJ	market for heat, district or industrial, natural gas (Europe without Switzerland)
Municipal solid waste	-3.00E-02	kg	market for municipal solid waste (RER)
Waste mineral oil	-1.61E-03	kg	market for waste mineral oil (EU without Switzerland)
Waste plastic	-1.19E+00	kg	market for waste plastic, mixture (RER)
Waste polyvinylfluoride	-1.10E-01	kg	market for waste polyvinylfluoride (CH)
Wastewater	-2.10E-02	kg	market for wastewater, average (Europe without Switzerland)
Panel EoL stage (BIPV) (per m^2) – 2022, 2030 and 2050			
Glass (waste)	2.02E+00	kg	market group for waste glass (Europe without Switzerland)
Glass (recycle)	8.08E+00	kg	waste packaging glass, unsorted, Recycled Content cut-off (GLO)
Copper (waste)	1.13E-01	kg	market for scrap copper (Europe without Switzerland)
Plastic (recycle)	6.71E-01	kg	market group for waste plastic, mixture (Europe without Switzerland)
Other waste	4.16E+00	kg	market for hazardous waste, for incineration (Europe without Switzerland)

Table 4.13: Inventory data for the PV mounting systems manufacturing and EoL stages (bifacial and monofacial systems) [32]

Environmental aspect	Value	Unit	LCI dataset
Mounting system manufacturing stage (bifacial and monofacial) (per m^2) – 2022, 2030 and 2050			
Aluminium	3.98E+00	kg	market for aluminium, wrought alloy (GLO)
Concrete	5.42E-04	kg	market for concrete, normal strength (GLO)
Polyethylene	9.09E-04	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Polystyrene	4.55E-03	kg	market for polystyrene, high impact (GLO)
Reinforcing steel	7.25E+00	kg	market for reinforcing steel (GLO)
Section bar extrusion	3.98E+00	kg	market for section bar extrusion, aluminium (GLO)
Section bar rolling	6.15E+00	kg	market for section bar rolling, steel (RER)
Steel	2.50E-01	kg	market for steel, chromium steel 18/8, hot rolled (GLO)
Wire drawing	1.10E+00	kg	market for wire drawing, steel (GLO)
Coils (zinc)	1.10E-01	m^2	market for zinc coat, coils (GLO)
Pieces (zinc)	1.52E-01	p	market for zinc coat, pieces (GLO)
Mounting system EoL stage(bifacial and monofacial) (per m^2) – 2022, 2030 and 2050			
Aluminium (waste)	3.58E+00	kg	market for scrap aluminium (Europe without Switzerland)
Aluminium (recycle)	3.98E-01	kg	recycling of aluminium (GLO)
Steel (waste)	7.25E-01	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	6.53E+00	kg	recycling of steel and iron (GLO)
Electric wiring (waste)	1.10E+00	kg	market for waste electric wiring (RoW)
Zinc (waste)	2.75E-01	kg	market for zinc slag (GLO)
Plastic (waste)	9.09E-04	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Polystyrene (waste)	4.55E-03	kg	market group for waste polystyrene (RER)

Table 4.14: Inventory data for the PV mounting systems manufacturing and EoL stages (floating systems) [30]

Environmental aspect	Value	Unit	LCI dataset
Mounting system manufacturing stage (floating systems) (per m^2) – 2022, 2030 and 2050			
Steel	3.98E+00	kg	market for steel, low alloyed (GLO)
Working metal	5.42E-04	kg	market for market for metal working, average for metal product manufacturing (GLO)
Hot rolling	9.09E-04	kg	market for hot rolling, steel (GLO)
Polyethylene	4.55E-03	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Injection moulding	7.25E+00	kg	market for injection moulding (GLO)
Concrete	3.98E+00	kg	market group for concrete, normal strength (GLO)
Mounting system EoL stage (floating systems) (per m^2) – 2022, 2030 and 2050			

Environmental aspect	Value	Unit	LCI dataset
Steel (waste)	5.41E-01	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	4.86E+00	kg	recycling of steel and iron (GLO)
Plastic (waste)	1.08E+01	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Plastic (recycle)	7.21E+00	kg	recycling of mixed plastics (GLO)

Table 4.15: Inventory data for the PV mounting systems manufacturing and EoL stage (BIPV systems) [33]

Environmental aspect	Value	Unit	LCI dataset
Mounting system manufacturing stage (BIPV systems) (per m^2) – 2022, 2030 and 2050			
Aluminium	3.27E+00	kg	market for aluminium, wrought alloy (GLO)
Section bar extrusion	3.27E+00	kg	market for section bar extrusion, aluminium (GLO)
Mounting system EoL stage (BIPV systems) (per m^2) – 2022, 2030 and 2050			
Aluminium (waste)	3.27E-01	kg	market for scrap aluminium (Europe without Switzerland)
Aluminium (recycle)	2.94E+00	kg	recycling of aluminium (GLO)

Table 4.16: Inventory data for the PV mounting systems manufacturing and EoL stages (BAPV systems) [33]

Environmental aspect	Value	Unit	LCI dataset
Mounting system manufacturing stage (BAPV systems) (per m^2) – 2022, 2030 and 2050			
Aluminium	2.84E+00	kg	market for aluminium, wrought alloy (GLO)
Polyethylene	1.40E-03	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Polystyrene	7.03E-03	kg	market for polystyrene, high impact (GLO)
Steel	1.50E+00	kg	market for steel, low alloyed (GLO)
Section bar extrusion	2.84E+00	kg	market for section bar extrusion, aluminium (GLO)
Hot rolling	1.50E+00	kg	market for hot rolling, steel (GLO)
Mounting system EoL stage (BAPV systems) (per m^2) – 2022, 2030 and 2050			
Aluminium (waste)	2.84E-01	kg	market for scrap aluminium (Europe without Switzerland)
Aluminium (recycle)	2.56E+00	kg	recycling of aluminium (GLO)
Steel (waste)	1.35E+00	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	1.50E-01	kg	recycling of steel and iron (GLO)
Plastic (waste)	1.40E-03	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Polystyrene (waste)	7.03E-03	kg	market group for waste polystyrene (RER)

Table 4.17: Inventory data for the electronic installation 1.3 MWp manufacturing and EoL stages (floating, bifacial and monofacial systems) [33]

Environmental aspect	Value	Unit	LCI dataset
Electronic installation manufacturing stage (floating, bifacial and monofacial systems) (per unit) – 2022, 2030 and 2050			
Brass	7.50E+00	kg	market for brass (GLO)
Copper	3.87E+03	kg	market for copper cathode (GLO) (Europe without Switzerland)
Resin	7.50E-01	kg	market for epoxy resin, liquid (RER)
Nylon	8.63E+01	kg	market for nylon 6 (GLO)
Polycarbonate	5.46E-02	kg	market for polycarbonate (GLO)
Polyethylene	3.73E+03	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Polyvinylchloride	2.36E+02	kg	market for polyvinylchloride, bulk polymerised (GLO)
steel, low-alloyed	2.90E+02	kg	market for steel, low-alloyed, hot rolled (GLO)
Wire drawing	3.87E+03	kg	market for wire drawing, steel (GLO)
Zinc	1.50E+01	kg	market for zinc (GLO)
Electronic installation EoL stage (floating, bifacial and monofacial systems) (per unit) – 2022, 2030 and 2050			
Copper	3.88E+03	kg	market for scrap copper (Europe without Switzerland)
Steel (waste)	2.90E+01	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	2.61E+02	kg	recycling of steel and iron (GLO)
Electric wiring (waste)	3.87E+03	kg	market for waste electric wiring (RoW)
Plastic (waste)	1.53E+03	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Plastic (recycle)	2.29E+03	kg	recycling of mixed plastics (GLO)
Polyvinyl chloride (waste)	9.44E+01	kg	market for waste polyvinylchloride product (Europe without Switzerland)
Polyvinyl chloride (recycle)	1.42E+02	kg	recycling of PVC (GLO)

Table 4.18: Inventory data for the electronic installation 93 kWp manufacturing and EoL stages (BIPV systems) [33]

Environmental aspect	Value	Unit	LCI dataset
Electronic installation manufacturing stage (BIPV systems) (per unit) – 2022, 2030 and 2050			
Brass	5.46E-01	kg	market for brass (GLO)
Copper	7.06E+01	kg	market for copper cathode (GLO) (Europe without Switzerland)
Resin	5.46E-02	kg	market for epoxy resin, liquid (RER)
Nylon	6.28E+00	kg	market for nylon 6 (GLO)
Polycarbonate	5.46E-02	kg	market for polycarbonate (GLO)
Polyethylene	6.07E+01	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Polyvinylchloride	8.69E+00	kg	market for polyvinylchloride, bulk polymerised (GLO)

Environmental aspect	Value	Unit	LCI dataset
steel, low-alloyed	2.24E+01	kg	market for steel, low-alloyed, hot rolled (GLO)
Wire drawing	7.06E+01	kg	market for wire drawing, steel (GLO)
Zinc	1.09E+00	kg	market for zinc (GLO)
Electronic installation EoL stage (BIPV systems) (per unit) – 2022, 2030 and 2050			
Copper	7.11E+01	kg	market for scrap copper (Europe without Switzerland)
Steel (waste)	2.24E+00	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	2.02E+01	kg	recycling of steel and iron (GLO)
Electric wiring (waste)	7.06E+01	kg	market for waste electric wiring (RoW)
Plastic (waste)	2.68E+01	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Plastic (recycle)	4.03E+01	kg	recycling of mixed plastics (GLO)
Polyvinyl chloride (waste)	3.48E+00	kg	market for waste polyvinylchloride product (Europe without Switzerland)
Polyvinyl chloride (recycle)	5.21E+00	kg	recycling of PVC (GLO)
Zinc (waste)	1.09E+00	kg	market for zinc slag (GLO)

Table 4.19: Inventory data for the electronic installation 3 kWp manufacturing (BAPV systems) [32]

Environmental aspect	Value	Unit	LCI dataset
Electronic installation manufacturing (BAPV systems) (per unit) – 2022, 2030 and 2050			
Brass	2.00E-02	kg	market for brass (GLO)
Copper	1.47E+01	kg	market for copper cathode (GLO) (Europe without Switzerland)
Resin	2.00E-03	kg	market for epoxy resin, liquid (RER)
Nylon	2.30E-01	kg	market for nylon 6 (GLO)
Polycarbonate	2.00E-01	kg	market for polycarbonate (GLO)
Polyethylene	1.44E+01	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Polyvinylchloride	2.13E+00	kg	market for polyvinylchloride, bulk polymerised (GLO)
steel, low-alloyed	8.60E-01	kg	market for steel, low-alloyed, hot rolled (GLO)
Wire drawing	1.47E+01	kg	market for wire drawing, steel (GLO)
Zinc	4.00E-02	kg	market for zinc (GLO)
Electronic installation EoL stage (BIPV systems) (per unit) – 2022, 2030 and 2050			
Copper	1.47E+01	kg	market for scrap copper (Europe without Switzerland)
Steel (waste)	8.60E-02	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	7.74E-01	kg	recycling of steel and iron (GLO)
Electric wiring (waste)	1.47E+01	kg	market for waste electric wiring (RoW)
Plastic (waste)	5.93E+00	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Plastic (recycle)	8.90E+00	kg	recycling of mixed plastics (GLO)

Environmental aspect	Value	Unit	LCI dataset
Polyvinyl chloride (waste)	8.52E-01	kg	market for waste polyvinylchloride product (Europe without Switzerland)
Polyvinyl chloride (recycle)	1.28E+00	kg	recycling of PVC (GLO)
Zinc (waste)	4.00E-02	kg	market for zinc slag (GLO)

Table 4.20: Inventory data for the inverter manufacturing and EoL stages (0.5 MVA) (floating, bifacial and monofacial systems) [32]

Environmental aspect	Value	Unit	LCI dataset
Invertor manufacturing stage (floating, bifacial and monofacial systems) (per unit) – 2022, 2030 and 2050			
Paint	2.20E+01	kg	market for alkyd paint, white, without solvent, in 60% solution state (RER)
Aluminium	1.31E+02	kg	market for aluminium, cast alloy (GLO)
Capacitor, electrolyte type, > 2cm	2.56E-01	kg	market for capacitor, electrolyte type, > 2cm height (GLO)
Capacitor, film type	3.41E-01	kg	market for capacitor, film type, for through-hole mounting (GLO)
Capacitor, tantalum	2.30E-02	kg	market for capacitor, tantalum-, for through-hole mounting (GLO)
Copper	3.35E+02	kg	market for copper, cathode (GLO)
Diode	4.70E-02	kg	market for diode, glass-, for through-hole mounting (GLO)
Electric connector	4.74E+01	kg	market for electric connector, wire clamp (GLO)
Fleece	3.00E-01	kg	market for fleece, polyethylene (GLO)
Polyamide	7.10E+01	kg	market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)
Polyester	4.40E+01	m^2	market for glass fibre reinforced plastic, polyester resin, hand lay-up (GLO)
Inductor	3.51E-01	p	market for inductor, ring core choke type (GLO)
Injection moulding	7.10E+01	kg	market for injection moulding (GLO)
Integrated circuit	2.80E-02	kg	market for integrated circuit, logic type (GLO)
lubricating oil	8.81E+02	kg	market for lubricating oil (RER)
Factory	1.36E-06	p	market for metal working factory (GLO)
Polyethylene	2.20E+01	kg	market for polyethylene, high density, granulate (Europe without Switzerland)
Polystyrene	1.60E+00	kg	market for polystyrene foam slab (GLO)
Printed wiring board	2.224E-01	m^2	market for printed wiring board, for through-hole mounting, Pb containing surface (GLO)
Resistor	5.00E-03	kg	market for resistor, metal film type, through-hole mounting (GLO)
Extrusion	1.31E+02	kWh	market for section bar extrusion, aluminium (GLO)
Sheet rolling	1.44E+03	MJ	market for sheet rolling, steel (GLO)
Steel	1.44E+03	kg	market for steel, low-alloyed, hot rolled (RER)

Environmental aspect	Value	Unit	LCI dataset
Transistor	3.80E-02	kg	market for transistor, wired, small size, through-hole mounting (GLO)
Wire drawing	3.35E+02	kg	market for wire drawing, copper (GLO)
Electricity	4.58E+03	kWh	market for electricity, medium voltage (Europe without Switzerland)
Invertor EoL stage (floating, bifacial and monofacial systems) (per unit) – 2022, 2030 and 2050			
Printed wiring boards (waste)	2.24E-01	kg	market for used printed wiring boards (GLO)
Lubricant (waste)	8.81E+02		market for used printed wiring boards (GLO)
Plastic (waste)	5.49E+01	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Plastic (recycle)	8.24E+01	kg	recycling of mixed plastics (GLO)
Polystyrene (waste)	1.60E+00	kg	market group for waste polystyrene (RER)
Copper	3.35E+02	kg	market for scrap copper (Europe without Switzerland)
Electronic (waste)	7.21E+01		market for electronics scrap from control units (GLO)
Electric wiring (waste)	3.82E+02	kg	market for waste electric wiring (RoW)
Aluminium (waste)	1.18E+02	kg	market for scrap aluminium (Europe without Switzerland)
Aluminium (recycle)	1.31E+01	kg	recycling of aluminium (GLO)
Steel (waste)	1.44E+02	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	1.30E+03	kg	recycling of steel and iron (GLO)

Table 4.21: Inventory data for the inverter manufacturing and EoL stages (0.01 MVA) (BIPV and BAPV) [33]

Environmental aspect	Value	Unit	LCI dataset
Invertor manufacturing stage (BIPV and BAPV systems) (per unit) – 2022, 2030 and 2050			
Aluminium	1.22E+01	kg	market for aluminium, cast alloy (GLO)
Aluminium (AlMg3)	5.43E-01	kg	market for aluminium alloy, AlMg3 (GLO)
Copper	4.90E+00	kg	market for copper, cathode (GLO)
Steel	2.33E+00	kg	market for steel, low-alloyed (GLO)
Polypropylene	2.27E+00	kg	market for polypropylene, granulate (GLO)
Polycarbonate	5.19E-01	kg	market for polycarbonate (GLO)
Cable (computer)	3.37E-01	m	market for cable, connector for computer, without plugs (GLO)
Inductor	2.58E+00	kg	market for inductor, ring core choke type (GLO)
Integrated circuit logic type	5.69E-01	kg	market for integrated circuit, logic type (GLO)
Ferrite	8.97E-02	kg	market for ferrite (GLO)
Plugs	9.65E+00	p	plug production, inlet and outlet, for network cable (GLO)
Polyamide	4.01E-01	kg	market for glass fibre reinforced plastic, polyamide, injection moulded (GLO)

Environmental aspect	Value	Unit	LCI dataset
Printed wiring board	2.60E-01	kg	market for printed wiring board, for surface mounting, Pb free surface (GLO)
Tin	2.46E-02	kg	market for tin (GLO)
Connector	6.26E-02	kg	market for electric kettle (GLO)
Integrated circuit memory type	4.81E-03	p	market for integrated circuit, memory type (GLO)
Transistor, wired	4.92E-02	kg	market for transistor, wired, small size, through-hole mounting (GLO)
Transistor	1.07E-01	kg	market for transistor, surface-mounted (GLO)
Diode	5.15E-03	kg	market for diode, glass-, for surface-mounting (GLO)
LED	3.69E-05	kg	market for light emitting diode (GLO)
Capacitor, film type	4.27E-01	kWh	market for capacitor, film type, for through-hole mounting (GLO)
Capacitor, electrolyte type, > 2cm	6.60E-01	MJ	market for capacitor, electrolyte type, > 2cm height (GLO)
Capacitor, electrolyte type, < 2cm	1.72E-02	kg	market for capacitor, electrolyte type, < 2cm height (GLO)
Capacitor	3.42E-03	kg	market for capacitor, for surface-mounting (GLO)
Resistor, wirewound	2.87E-03	kg	market for resistor, wirewound, through-hole mountin (GLO)
Resistor	1.17E-02	kg	market for resistor, surface-mounted (GLO)
Transformer	1.03E-01	kg	market for transformer, low voltage use (GLO
Cable	6.16E-04	kg	market for cable, ribbon cable, 20-pin, with plugs (GL)
Sheet rolling	2.33E+00	kg	market for sheet rolling, steel (GLO)
Wire drawing	4.90E+00	kg	market for wire drawing, copper (GLO)
Extrusion	1.22E+01	kg	market for section bar extrusion, aluminium (GLO)
Metal working	4.93E-02	kg	market for metal working, average for steel product manufacturing (GLO
Factory	2.82E-08	p	market for metal working factory (GLO)
Tap water	5.10E+01	kg	market for tap water (Europe without Switzerland)
Electricity	2.71E+01	kWh	market for electricity, medium voltage (Europe without Switzerland)
Heat	2.36E+01	MJ	market for heat, district or industrial, natural gas (Europe without Switzerland)
Invertor EoL stage (floating, bifacial and monofacial systems) (per unit) – 2022, 2030 and 2050			
Printed wiring boards (waste)	2.60E-01	kg	market for used printed wiring boards (GLO)
Plastic (waste)	1.28E+00	kg	treatment of waste polyethylene/polypropylene product, collection for final disposal (Europe without Switzerland)
Plastic (recycle)	1.91E+00	kg	recycling of mixed plastics (GLO)
Polystyrene (waste)	4.90E+00	kg	market group for waste polystyrene (RER)
Copper	1.44E+01	kg	market for scrap copper (Europe without Switzerland)
Electronic (waste)	5.24E+00		market for electronics scrap from control units (GLO)

Environmental aspect	Value	Unit	LCI dataset
Electric wiring (waste)	2.60E-01	kg	market for waste electric wiring (RoW)
Aluminium (waste)	1.27E+00	kg	market for scrap aluminium (Europe without Switzerland)
Aluminium (recycle)	1.15E+01	kg	recycling of aluminium (GLO)
Steel (waste)	2.33E-01	kg	market for scrap steel (Europe without Switzerland)
Steel (recycle)	2.10E+00	kg	recycling of steel and iron (GLO)

Table 4.22 displays inventory data of the transportation of components from the manufacturing to the installation and the EoL stages. These data have been calculated assuming an average distance of 500 km for all scenarios for both stages (transportation between the manufacturing and installation stages and transportation between the installation and the EoL stages).

Notably, the values in the table are similar for all three climatic zones considered. However, they vary significantly depending on the time horizons analysed, as these determine the plant's lifespan. Also, it is important to note that the data in the table are expressed in terms of 1m² of PV system (reference unit), considering the system lifespan.

Table 4.22: Inventory data for the transportation stages

Enviro. aspect	Value			Unit	LCI dataset
Transportation between manufacturing and installation stage (per m^2) – Lappeenranta, Munich and Murcia					
System	**2022**	**2030**	**2050**		**Simapro**
Floating	7.70E-01	5.93E-01	6.10E-01	tkm	market for transport, freight, lorry >32 metric ton, EURO5
Bifacial	5.20E-01	4.05E-01	4.22E-01	tkm	market for transport, freight, lorry >32 metric ton, EURO5
Monofacial	4.41E-01	3.46E-01	3.62E-01	tkm	market for transport, freight, lorry >32 metric ton, EURO5
BIPV	2.34E-01	2.37E-01	2.00E-01	tkm	market for transport, freight, lorry >32 metric ton, EURO5
BAPV	3.16E-01	2.46E-01	2.18E-01	tkm	market for transport, freight, lorry >32 metric ton, EURO5

Table 4.23 and **Table 4.24** provide comprehensive information related to the installation and operation and maintenance stages, respectively. The values for energy consumption, specifically electricity and diesel, have been calculated for the installation stage. Additionally, land use and transformation data have been included for scenarios involving ground-mounted PV installation technologies. These calculations have been performed using the Ecoinvent database. On the other hand, **Table 4.24** consolidates the data pertaining to the operation phase of PV technologies and their maintenance requirements. Similar to the installation phase, these values have also been derived using information from the Ecoinvent database.

Table 4.23: Inventory data for the installation stage [33]

Environmental aspect	Value				Unit	LCI dataset
Installation stage (per m^2) – Lappeenranta, Munich and Murcia						
System	**Floating**	**Bifacial**	**Monofacial**	**BIPV**	**BAPV**	**Unit**
Electricity	8.18E-03	8.18E-03	8.18E-03	8.33E-04	8.33E-04	kWh
Heat	1.74E+00	1.74E+00	1.74E+00	-	-	Mj
Transformation, from pasture and meadow	-	4.58E+00	4.58E+00	-	-	m^2

Environmental aspect	Value				Unit	LCI dataset
Transformation, to industrial area, built up	-	1.46E+00	1.46E+00	-	-	m^2
Transformation, to industrial area, vegetation	-	3.13E+00	3.13E+00	-	-	m^2
Occupation, industrial area, built up	-	4.37E+00	4.37E+00	-	-	m^2a
Occupation, industrial area, vegetation	-	9.67E+00	9.67E+00	-	-	m^2a

Table 4.24: Inventory data for the operation and maintenance stages [33]

Environmental aspect	Value				Unit	LCI dataset
Operation stage (per kWh) – Lappeenranta, Munich and Murcia						
System	**Floating**	**Bifacial**	**Monofacial**	**BIPV**	**BAPV**	**Unit**
Energy, solar, converted	3.85E+00	3.85E+00	3.85E+00	3.85E+00	3.85E+00	kWh
Maintenance stage (per kWh) – Lappeenranta, Munich and Murcia						
	Floating	**Bifacial**	**Monofacial**	**BIPV**	**BAPV**	**Unit**
Tap water	2.20E-05	2.20E-05	2.20E-05	5.51E-03	4.02E-03	kg
Wastewater	2.20E-08	2.20E-08	2.20E-08	5.51E-06	4.02E-06	m^3

5 LIFE CYCLE IMPACT ASSESSMENT: RESULTS AND DISCUSSION

The environmental analysis results have been divided into several parts:

- ***Hotspot analysis***: This analysis includes an evaluation of innovative technologies (floating, bifacial, and BIPV). For these, the impacts of each stage (manufacturing, transportation to the installation site, plant installation, plant operation, plant maintenance, transportation at the EoL, and EoL of the plant) have been analysed. Additionally, the impacts of the stage with the highest impact have also been examined.
- ***Comparative analysis***: The three innovative technologies have been compared with conventional technologies (monofacial and BAPV). Furthermore, various comparisons have been made considering the three climatic and time horizons.
- ***Integration of technologies into the power grid***: Projections have been made of the composition of energy types that could be present in the grid energy mix for 2022, 2030, and 2050 to observe the evolution and potential environmental performances.
- ***Analysis of KSIs:*** A list of indicators has been selected for analysis.
- ***Analysis Considering Innovations***: A sensitivity analysis has been conducted to see how the innovations developed in the project would impact environmental impacts. This analysis considered an increase in the performance ratio (PR) by 0.5%, 1%, 2%, and 3%.
- ***Synopsis to prospective LCA of the technologies:*** An in-depth literature review on the application of pLCA in solar photovoltaic technologies is conducted through academic research platforms and existing pLCA tools and LCIs are examined to anticipate the technology difference in pLCA tools. This section highlights the limitations of pLCA tools concerning the divergence in future assumptions and the LCIs of solar photovoltaic technologies.

This comprehensive environmental analysis provides valuable insights into the impacts and benefits of innovative solar technologies. Understanding these effects across different stages and comparing them with conventional methods allows for better-informed decisions and policies to promote sustainable energy solutions. Integrating these technologies into the grid and considering future innovations further highlight the potential for improving environmental outcomes over time.

5.1 Hotspot analysis

5.1.1 By stage

The hotspot analysis has focused on three specific time horizons: 2022, 2030, and 2050, but only for Murcia, because the trend with the other scenarios is similar. This analysis has evaluated the environmental impact across several key categories, which include: the manufacturing of PV panels, transportation to the installation site, system operation, system maintenance, transportation to EoL, and the EoL stage itself.

Figure 5.1 shows the environmental impact generated by the floating system. The results have shown that the manufacturing PV stage has the highest environmental impact, followed by the EoL, transportation, and plant installation stages. The operation and maintenance stages have had the lowest environmental impact. Notably, the operation stage has zero impact across all categories because, during this stage, no raw materials have been consumed, and no emissions or waste have been generated.

Additionally, this trend has been consistent regardless of the time horizon considered. Specifically, the average environmental impact in the manufacturing stage has exceeded 96%, whereas the EoL stage has accounted for approximately 2% of the impact. The other stages, including transportation, installation and maintenance, have had less than 0.6% impacts.

Moreover, the characterized results presented in **Table S.3** have revealed a decreasing trend in the environmental impact over time for all stages and across nearly all impact categories. For example, in the GW category, the environmental impact has been significantly reduced from 3.02E-02 kg CO_2 eq/kWh in 2022 to 1.83E-02 kg CO_2 eq/kWh in 2030 and further down to 1.75E-02 kg CO_2 eq/kWh by 2050.

This analysis has highlighted the importance of focusing on the manufacturing process to reduce the overall environmental impact of PV systems. The significant reduction in impact over time has highlighted advancements in technology and processes that contribute to more sustainable practices in the PV industry. It has also emphasized the potential benefits of continued innovation and improvements in the lifecycle management of PV systems to achieve better environmental outcomes in the future.

Figure 5.1: Environmental hotspot analysis of floating PV technology in Murcia: 2022, 2030 and 2050

Figure 5.2 shows the results for bifacial PV technology. Similar to the case of floating PV technology, it has been observed that the manufacturing stage has the highest environmental impact, with an average of approximately 91%. However, due to the land use and transformation required to install bifacial panels, the average impact has increased significantly to about 6%. This has been because, in the LU category, the impact exceeds 95%. If this impact category is excluded, the average impact of the installation stage would decrease to approximately 0.06%.

As with floating PV technologies, the EoL stage has had a relatively low average impact of approximately 1.7%. The other stages, including transportation, operation, and maintenance, have had the least impact, all of them contributing less than 1% to the overall environmental impact.

Furthermore, the characterized results presented in **Table S.7** indicate that over time, the environmental impact decreases for all stages across almost all impact categories. For example, in the GW category, the environmental impact has been significantly reduced from 2.60E-02 kg CO_2 eq/kWh in 2022 to 1.55E-02 kg CO_2 eq/kWh in 2030, and further down to 1.49E-02 kg CO_2 eq/kWh by 2050.

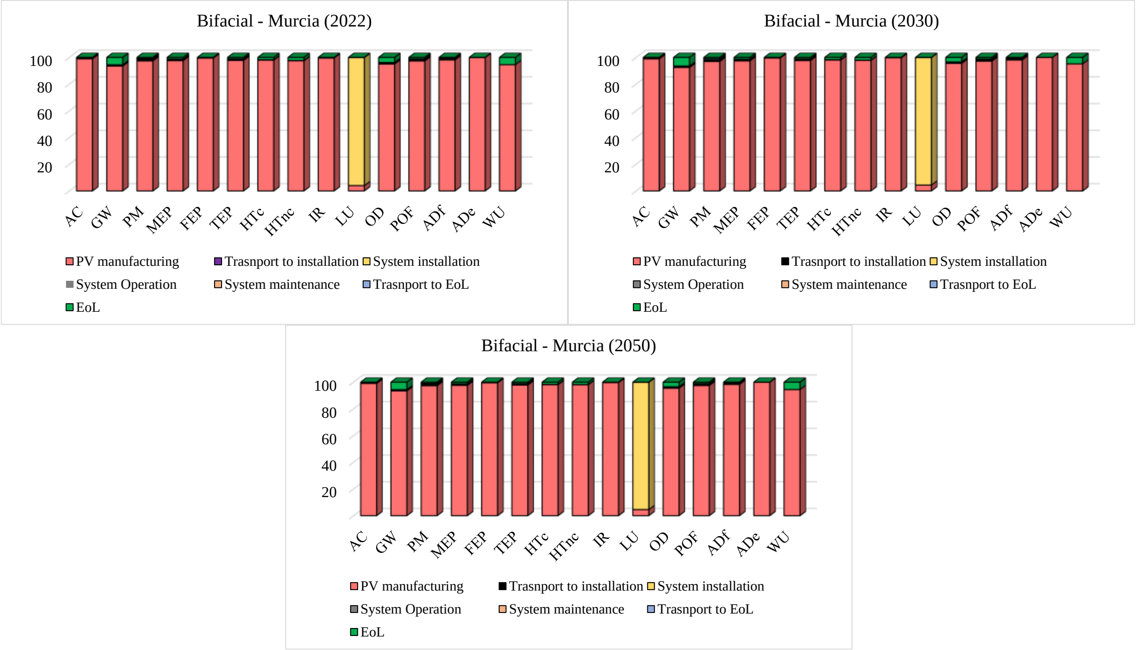


Figure 5.2: Environmental hotspot analysis of ground-mounted bifacial PV technology in Murcia: 2022, 2030 and 2050

For BIPV technology, the trends have been similar to those observed in the case of floating PV technology (**Figure 5.3**). However, for BIPV, the environmental impact of the manufacturing stage has been even more pronounced, exceeding 98.7%. In contrast, the impact of the EoL stage ranges between 1.37% and 1.60%. The combined impact of the remaining stages has been less than 0.6%.

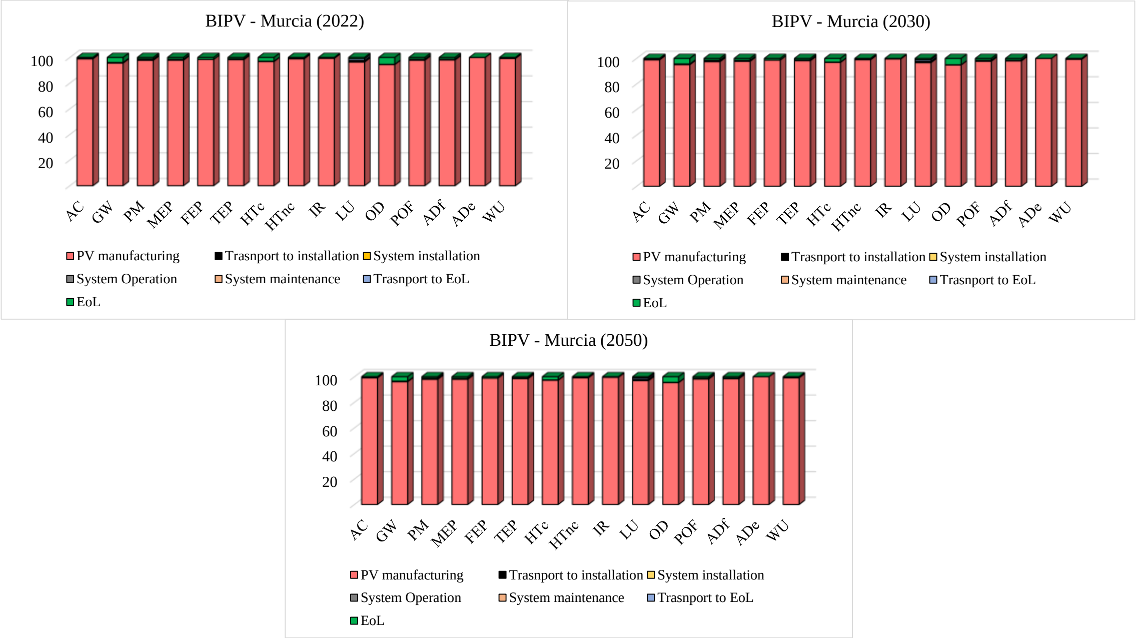


Figure 5.3: Environmental hotspot analysis of BIPV technology in Murcia: 2022, 2030 and 2050

In addition, the detailed results presented in **Table S.14** show a consistent decline in the environmental impact over time for all stages across nearly all categories. For example, in the GW category, the environmental impact has significantly decreased from 4.46E-02 kg CO_2 eq/kWh in 2022 to 3.47E-02 kg CO_2 eq/kWh in 2030, and further down to 2.79E-02 kg CO_2 eq/kWh by 2050.

The significant reduction in impact over time has highlighted the advances in technology and processes that promote more sustainable practices in the PV industry. It has also highlighted the potential benefits of ongoing innovation and improvements in the lifecycle management of PV systems to achieve better environmental outcomes in the future. However, these results have underscored the importance of focusing on the manufacturing process to reduce the overall environmental impact of PV systems. As a result, a hotspot analysis has been conducted, considering the manufacturing of the components included in the plant: cells, panels, mounting system, electronic installation, and inverter.

5.1.2 By manufactured components

Figure 5.4 and **Table S.4** show the results of the hotspot analysis for the manufacturing stage of components included in floating technology. It should be noted that the results of this analysis correspond to the production of the entire installed plant. Due to the consideration of the whole plant, the surface areas have varied across the different temporal horizons: 93,896 m² for 2022, 84,033 m² for 2030, and 66,667 m² for 2050. These differences in surface area have been related to the efficiency of the cells, which has increased from 21.3% in 2022 to 30% in 2050 (**Table 4.2**). It is also important to highlight that, for other components, no differences in manufacturing methods have been considered; therefore, the same data has been used throughout the different time horizons.

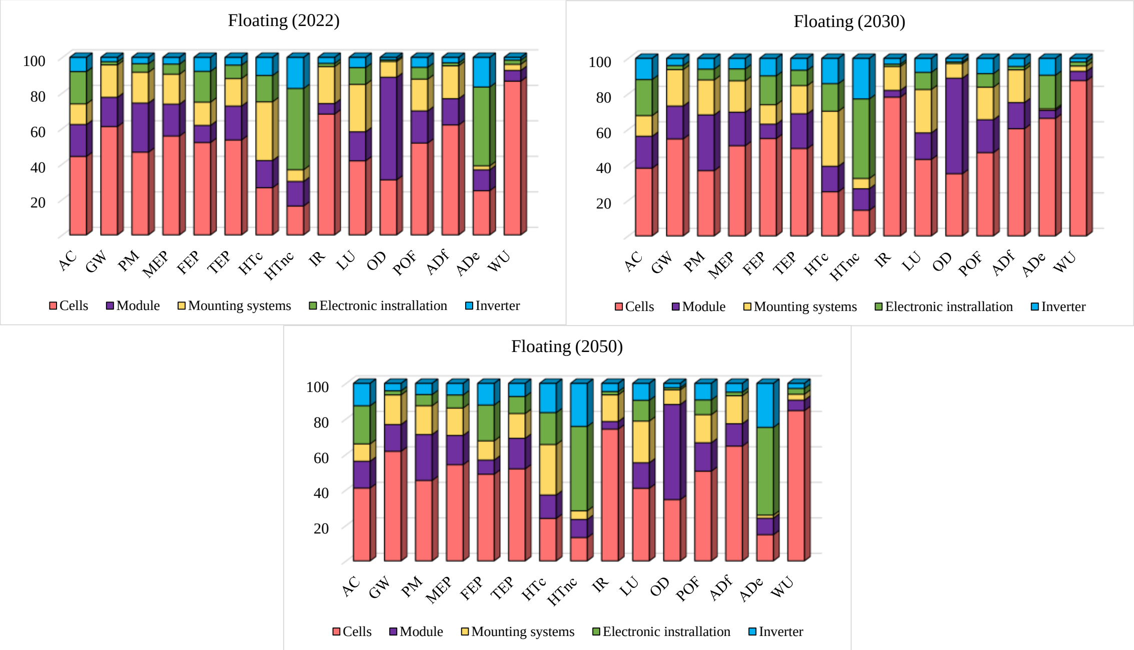


Figure 5.4: Environmental hotspot analysis of floating component manufacturing in Murcia: Projections for 2022, 2030, and 2050

The results have demonstrated that the cells significantly impacted almost all impact categories, averaging 48.1% for 2022, 49.4% for 2030, and 46.9% for 2050. As explained previously, different types of cells have been considered for each time horizon. Consequently, perovskite cells have been more sustainable than the other two types of cells. The most notable impact categories in this context have been GW, categories related to eutrophication (MEP, FEP, and TEP), IR, ADff, and WU.

The results in **Figure 5.4** have indicated that the high value in GW could been closely related to the generation of CO_2, N_2O and CH_4 emissions. These emissions are linked to electricity production (background processes) and its use (foreground processes) during cell manufacturing. In electricity production, fossil fuel extraction and use are the primary sources of GHG.

The EP categories (MEP, FEP, and TEP) have been significantly affected by the use of electricity and the background processes associated with electricity production. These background processes include the extraction and use of fossil fuels, as well as the production of mining waste. Power plants that use fossil fuels like coal, oil, and natural gas emit NOx and PO_4, which can contribute to EP.

Regarding IR, it has been observed that its impact has been closely linked to the use of electricity in cell production and the production of electricity itself. These processes generate significant emissions, including radon, cesium, cobalt, and other pollutants. The emissions of radon, cesium, and cobalt primarily result from the combustion of fossil fuels in power plants and other industrial processes and contribute to the overall environmental and health impacts.

In the case of ADf, this category has been affected by the use of oil, gas, and coal, raw materials used in electricity production (background processes). These resources are essential for the generation of energy and the operation of machinery. However, the extraction and combustion of oil, gas and coal to generate electricity contribute to environmental degradation and the depletion of non-renewable resources.

The impact in the WC category has been closely related to the use of deionized water and the production and use of silicone in cell manufacturing. Deionized water is a critical resource used in various stages of cell manufacturing. Its usage has contributed significantly to the overall water consumption associated with the production of cells. While deionized water does not generate direct environmental risks, the large quantities required can strain local water resources and increase energy consumption for water treatment and purification. On the other hand, silicone is a critical material in producing solar cells. The production of silicone can have significant environmental impacts, including energy consumption, GHGs, and the generation of waste and wastewater, but also water use.

Additionally, the ADe category has shown a significant impact for the 2030 scenario at 66.2%, which has been considerably higher than the other two scenarios (14.7% for 2022 and 24.9% for 2050). This has been primarily related to the use of metals such as gold and silver, which are essential for producing active electronic components. The extraction and processing of these metals entail an intense demand for energy and resources.

However, over time, there has been a general trend of decreasing the environmental impact of cell manufacturing across most categories, with the best results observed for 2050. However, it has been noteworthy that, for instance, in the AC, GW and PM categories, the cells used in the 2050 scenario have had a higher impact than those in 2030 but lower than in 2022.

In addition, the results demonstrated that while the impact of the modules has been lower than that of the cells, they are the second highest impact component, averaging 17.9% for 2022, 17.1% for 2030, and 25.8% for 2050. The most notable impact categories for the modules have been PM (27.7% for 2022, 31.4% for 2030, and 15.8% for 2050) and OD (57.8% for 2022, 53.8% for 2030, and 53.6% for 2050) (**Figure 5.4**). Additionally, it has been observed that, over time, the environmental impact decreases across all impact categories, with the best results achieved by 2050. This reduction has been primarily due to fewer modules needed due to the increasing efficiency of the cells, reducing the consumption of raw materials used in their production.

In the PM category, the impact of the modules primarily comes from PM <2.5µm emissions. These emissions have been closely related to the use and production of electricity and the production of flat glass used in manufacturing solar panels. PM <2.5 µm particles, also known as fine particles, are particularly concerning because they can cause health problems. During electricity production, especially when fossil fuels like coal and natural gas are used, large amounts of these fine particles are released into the air. Flat glass manufacturing has also significantly contributed to PM <2.5 µm emissions. This industrial process involves melting and forming the glass, which generates fine particle emissions and other air pollutants. If derived from fossil fuels, The energy required to produce this glass adds an additional load of PM emissions.

On the other hand, in the OD category, the manufacturing of solar modules has been the component with the highest impact. This impact has been primarily due to background processes involving terephthalic acid, which is used in the production of certain plastics and polyester resins and polyethylene terephthalate for the module encapsulation and other components. Additionally, the release of methane, bromo-, and halon

1001 during manufacturing processes has contributed significantly to OD impact. Bromo- and halon 1001 are chemicals that have been identified as ozone-depleting substances.

The mounting system has been the third component with the highest impact. Over time, its average impact has been slightly lower than the electrical components. For this component, the most significant impacts have been observed in HTc (33.1% for 2022, 31% for 2030, and 28.5% for 2050) and LU categories (26.7% for 2022, 24.4% for 2030, and 23.5% for 2050). The environmental impact of the mounting system has remained relatively stable over the years. However, there has been a slight decrease in impact due to reduced plant dimensions as cell efficiency increases over time.

In the case of HTc, the impact has been due to the emission of metals, including chromium, benzopyrene, and formaldehyde, and background processes such as the treatment of electric arc furnace slag, basic oxygen furnace slag, coke production, and other types of waste. These emissions and processes could contribute significantly to human toxicity by releasing carcinogenic substances into the environment. Regarding LU, the impact has been primarily related to background processes, especially the construction of roads.

The impact of the electrical installations has been relatively significant, generating an average total impact of 12.2% for 2022, 10.9% for 2030, and 14% for 2050. The main impact categories for electrical installations have been HTnc (44.4% for 2022, 45.8% for 2030, and 47.6% for 2050), ADe (44.4% for 2022, 18.9% for 2030, and 49.4% for 2050), and AC categories (18.2% for 2022, 20.3% for 2030, and 21.5% for 2050). Thus, considering the characterized values, the impact of the electrical components has been almost equal regardless of the time horizon.

In the case of HTnc, the impact has been due to the emission of metals, including lead, arsenic, and cadmium, as well as the consumption of copper. These metals are released during various stages of production and usage, posing significant non-carcinogenic health risks. The ADe impact has been primarily related to the use of copper. Copper is a crucial material in electrical installations due to its excellent conductivity, but its extraction and processing lead to the depletion of minerals and metals. The AC impact has been primarily related to the use of copper and the generation of emissions such as SO_2, NOx, and NH_3, emissions that result from the mining, refining, and manufacturing processes associated with copper.

Finally, the inverters have been the components with the lowest impact across the scenarios, with impacts remaining below 10%. The results have shown that inverters substantially impact HTnc and ADe more due to copper use, production, and generated waste. The environmental impact of inverters has been decreased in 2030 and 2050 compared to 2022.

Figure 5.5 and **Table S.8** show the hotspot analysis results for the manufacturing stage of components included in bifacial technology. The surfaces in this case have been higher than in the case of the floating system: 234,741 m^2 for 2022, 210,084 m^2 for 2030, and 166,665 m^2 for 2050. These differences in the surface area have been related to the efficiency of the cells and the plant capacity, which in the case of floating technology has been 20 MWp (**Table 4.2**), while for bifacial systems, it has been 50 MWp (**Table 4.3**). The results between the floating system and the bifacial system have been relatively similar.

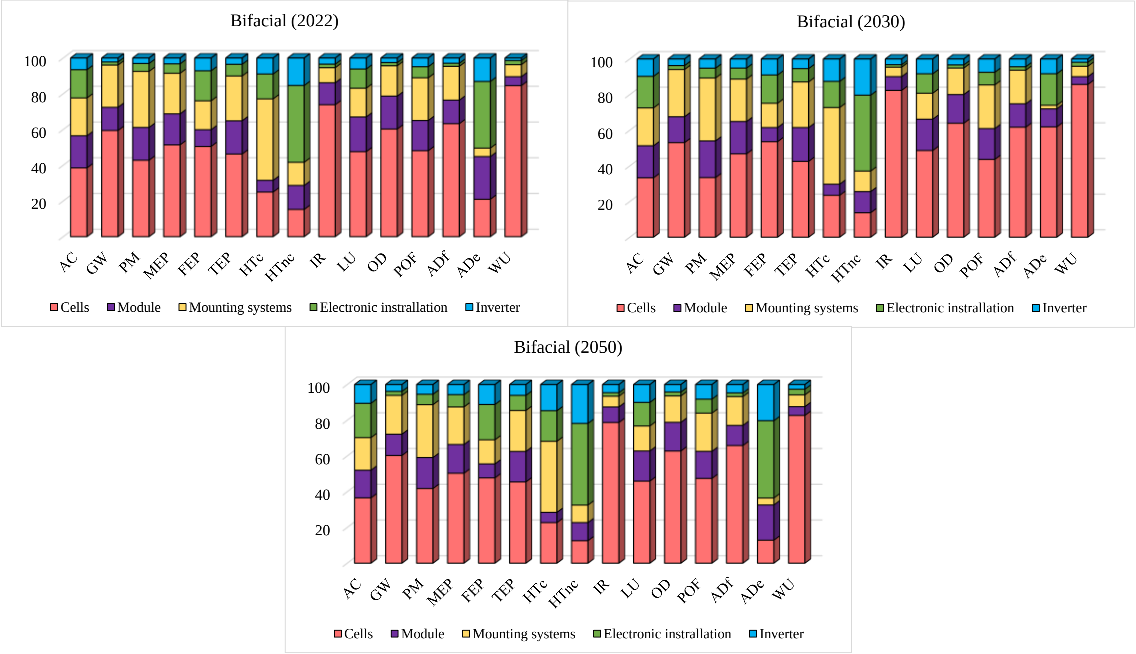


Figure 5.5: Environmental hotspot analysis of bifacial component manufacturing in Murcia: Projections for 2022, 2030, and 2050

The results have demonstrated that the cells significantly impacted almost all impact categories, averaging 48.5% for 2022, 49.9% for 2030, and 47.6% for 2050. Perovskite cells have been more sustainable than the other two types of cells. The most notable impact categories in this context have GW, MEP, FEP, TEP, IR, LU, OD, POF, ADff, and WU. These impacts, as in the case of the floating systems, have been due to the use and production of electricity (background processes: extraction and mining of fossil fuels), use and production of chemicals such as sodium hydroxide, chlorine, silver, and zinc, among others, but also to emissions generated during the production processes of electricity and chemicals.

In contrast to the floating scenarios, the results have demonstrated that the mounting system has been the second highest impact component, averaging 19.6% for 2022, 19.1% for 2030, and 19.3% for 2050. Over time, its average impact has decreased slightly. The most significant impacts for this component have been observed in HTc and PM. These impacts have been related to using and producing electricity, zinc, or aluminium, and the waste generated in background processes such as coke and slag.

In the case of the bifacial scenarios, the modules and the electronic installation have had relatively similar impacts in terms of overall categories. However, the modules have had higher impacts in PM, EP categories, LU, and ADe, while the electronic components have had higher impacts in HTnc and ADe. The impacts generated by the modules have been related to the use and production of electricity, flat glass, and copper. In contrast, the impacts of the electronic components have been driven by the use and production of copper and tin.

Finally, the inverters have been the components with the lowest impact across the scenarios, with impacts remaining below 10%. The results have shown that inverters have had a more substantial impact on HTc, HTnc, and ADe due to copper use, production, and generated waste.

Figure 5.6 and **Table S.15** shows the results of the hotspot analysis for the manufacturing stage of components included in BIPV technology. As in the case of the previous scenarios, it should be noted that the results of this analysis correspond to the production of the entire installed surface and correspond to 246 m² for 2022, 216 m² for 2030, and 172 m² for 2050. These installed surfaces have been related to the efficiency of the cells (18.9% for 2022, 21.4% for 2030 and 27.0% for 2025) and the plant capacity (0.0463 MWp) (**Table 4.5**).

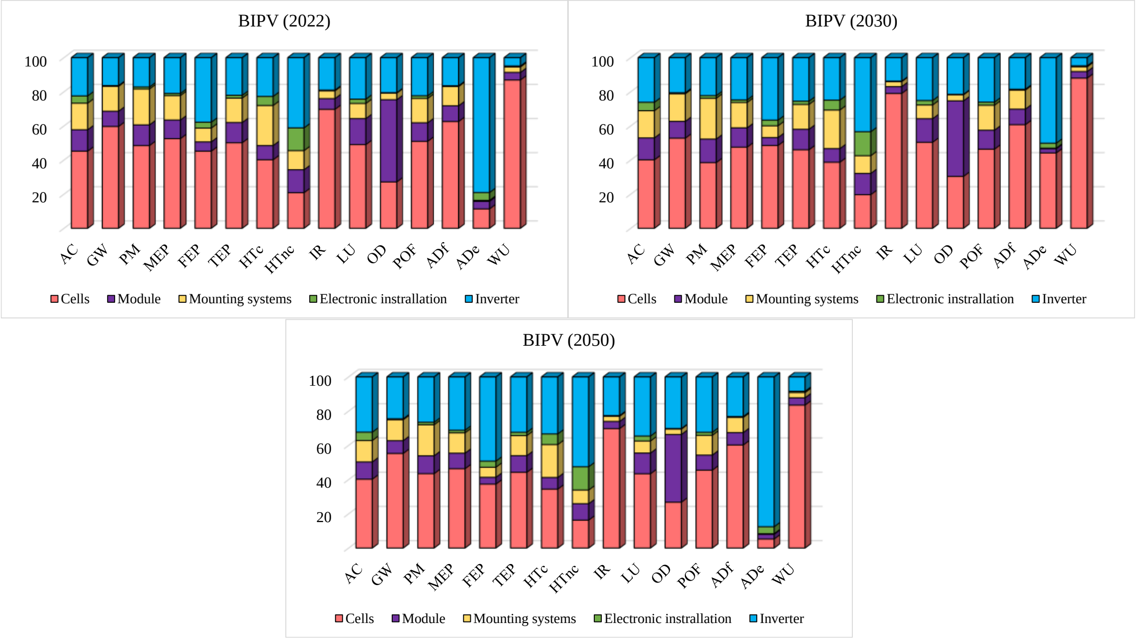


Figure 5.6: Environmental hotspot analysis of BIPV component manufacturing in Murcia: Projections for 2022, 2030, and 2050

The results have shown that the two components that most damage the environment have been the cells and the inverter. In this sense, solar cells have been the component with the highest environmental impact, registering the highest values in 12 of the 15 impact categories evaluated. The results have shown that solar cells contribute 48% of the total impact in 2022, 48.7% in 2030 and 43.5% in 2050, generating a high impact, especially in WC, IR, ADf and GW. This significant impact has been mainly due to the use and production of energy, silicon and water, among other factors. However, a decreasing trend has been observed in the impact of solar cells over time, which can be attributed to improvements in cell efficiency and technological advances, which allow higher generation of electrical energy. Perovskite cells, in particular, have been found to be more sustainable compared to other types of solar cells.

On the other hand, the inverter, the second most impactful component, has shown an average impact of 25.8% in 2022, 25.6% in 2030, and 34.7% in 2050. The inverter's main impacts have been observed in HTnc, ADe, and FEP (2050). These impacts have been related to the consumption and production of energy and materials such as copper and gold used in the inverter components. Temporal analysis has shown that the impact of the inverter has remained constant in the first two time horizons, increasing by 2050. This increase has been due to the consideration of a plant lifespan of 50 years in 2050, compared to 40 years in 2022 and 2030. This has implied an additional charge from investors since its useful life was supposed to have been 20 years.

In the BIPV scenario, modules and mounting systems have shown relatively similar global impacts, ranging from 9.1% to 12.1%, with slightly higher values for the modules. The modules have had high impacts in the categories of OD, PM, AC, and LU, due to the consumption and production of electricity, flat glass, copper, electricity and plastic components, among others. On the other hand, mounting systems have had high values in PM and HTc, due to the consumption and production of aluminium and electricity.

Finally, electronic installations have been found to have the least environmental impact, with consistent impact across different time horizons. The category most affected has been HTnc at around 13.5%, followed by AC and ADe, with relatively lower impacts of around 4.5%. The use and production of copper have mainly generated these impacts.

The analysis has revealed that solar cells have primarily contributed to environmental impacts across most categories due to their production and use of energy, silicon, and water. Perovskite cells, in particular, have shown promise as a more sustainable option than other cell types. Modules and mounting systems have had notable impacts in some categories due to the use and production of electricity, flat glass, zinc, or aluminium, among others. Inverters have also impacted the environment, especially in the BIPV scenarios, mainly through using copper and gold in their components. In contrast, although generally having less impact, electronic components have continued to contribute to environmental damage due mainly to the use and production of copper. However, over time, the environmental impacts of most components have decreased due to improvements in efficiency and technological advancements.

To mitigate these environmental impacts, transitioning to perovskite solar cells should be prioritized due to their lower environmental footprint [34,35]. Enhancing the efficiency and durability of inverters can also reduce their overall impact [36]. Optimizing the production processes of modules, particularly in reducing emissions from flat glass manufacturing, and implementing robust recycling programs for PV components can further decrease the environmental burden [37,38]. These steps, along with continuous monitoring and stricter environmental regulations, will help ensure the PV industry evolves towards more sustainable practices [39].

5.2 Comparative analysis

5.2.1 By climatic zones

Figure 5.7 presents a comprehensive comparative analysis of the LCA of three PV technologies: floating PV, bifacial and BIPV. This analysis has been conducted in three sites (Lappeenranta, Munich and Murcia) and for three-time horizons (2022, 2030 and 2050). The results provide a detailed view of the environmental performance of each technology under different climatic conditions.

The comparative LCA analysis of the three PV technologies has shown similar trends regardless of the scenario, highlighting how site-specific factors significantly influence the environmental performance of PV systems. Overall, Lappeenranta has presented consistently higher environmental impacts in all categories compared to Munich and Murcia. This pattern has been mainly attributed to Lappeenranta's lower annual global tilted irradiation rate due to its geographical location in northern Europe.

For floating PV technology, environmental impacts have decreased by 23% in Munich and 48% in Murcia compared to Lappeenranta. In the case of bifacial technology, impacts have been reduced by 22% in Munich and 45% in Murcia compared to Lappeenranta. Finally, for BIPV technology, the impacts have decreased by 20% in Munich and 43% in Murcia compared to Lappeenranta. These differences have been occasioned due to the annual inclined global solar irradiance increasing from north to south, as shown in **Table 4.2**, **Table 4.3** and **Table 4.5**. In Lappeenranta, the irradiation for floating technology has been 21% and 47% lower than in Munich and Murcia, respectively. For bifacial technology, irradiation has been 18% and 44% lower in Lappeenranta than in Munich and Murcia, respectively. Regarding BIPV technology, irradiation has been 11% and 35% lower in Lappeenranta than in Munich and Murcia [40].

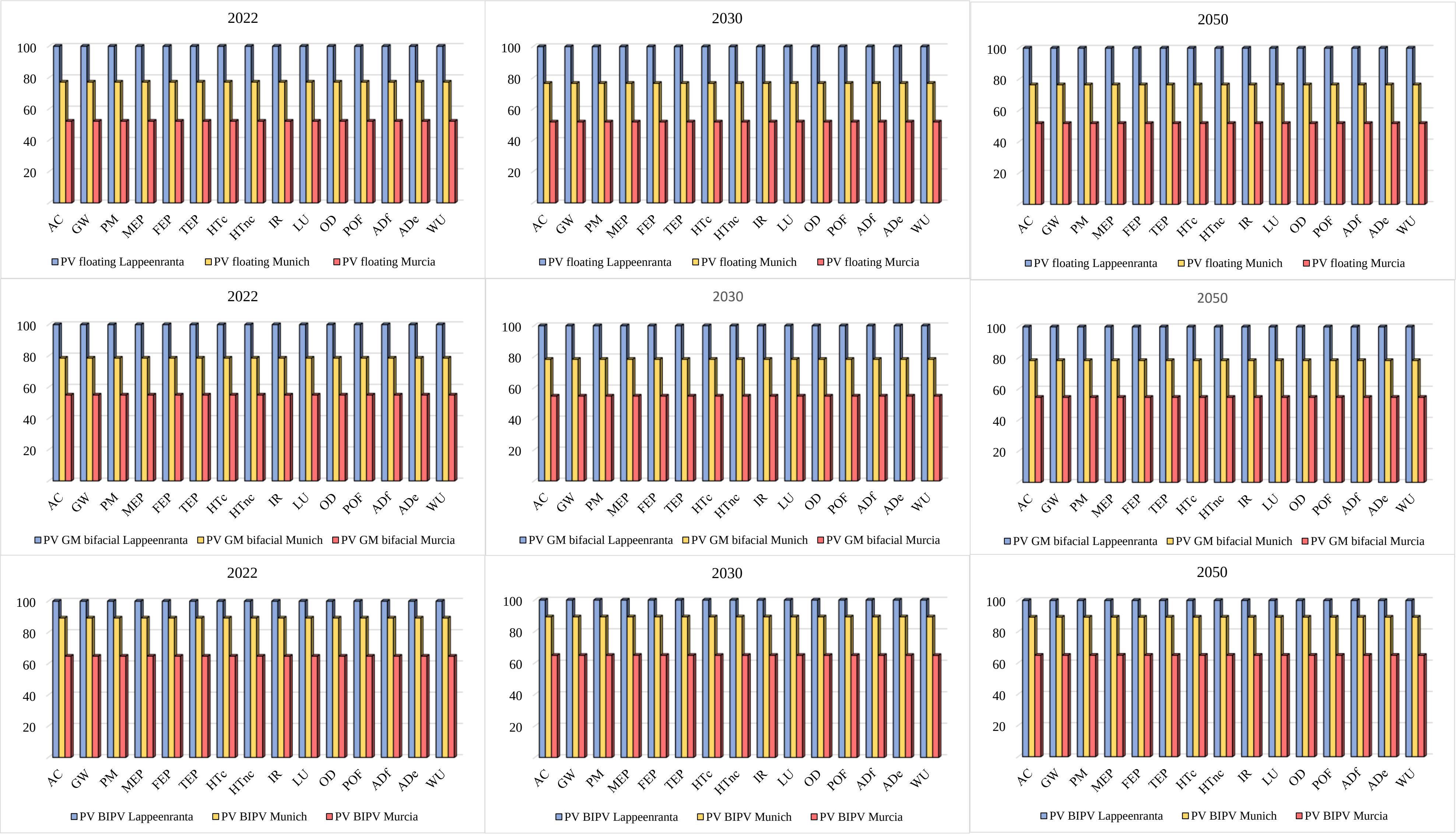


Figure 5.7: Comparative LCA of floating PV, bifacial, and BIPV technologies across varied climatic zones

Solar irradiation levels directly influence the amount of annual energy that can be generated with each PV technology [41,42]. The greater the solar irradiance, the greater the amount of energy that can be produced, which reduces the relative environmental impact of energy generation. This effect has been especially notable when comparing different geographic locations. In regions with high solar irradiance, PV systems can convert more sunlight into electricity, improving overall system efficiency. Additionally, greater energy production from PV systems means that less infrastructure is needed to generate the same amount of electricity, reducing the use of materials and resources, as well as the emissions associated with the manufacturing and maintenance of these systems [41,42]. On the other hand, increased energy generation can also reduce dependence on non-renewable energy sources, reducing GHGs and other pollutants associated with the use of fossil fuels.

Due to the high solar irradiation in Murcia, PV systems can generate a higher amount of energy, which is translated into greater efficiency and a lower environmental impact per unit of energy produced. With its sunny climate and abundant sunlight, Murcia allows PV panels to operate optimally for most of the year. This not only improves the economic viability of solar projects but also reduces the carbon footprint of energy production in the region. In contrast, in places like Lappeenranta, where solar irradiation is considerably lower, energy production is limited, resulting in higher relative environmental impacts. In these regions, PV systems need to be supplemented with other energy sources to meet demand, which can increase the complexity and costs of the global energy system [43,44]. Furthermore, the lower efficiency of solar panels in areas with low irradiance may require a larger installation surface to generate the same amount of energy, thus increasing costs and the environmental impact of land occupation.

In summary, the results of the LCA analysis have highlighted the importance of considering site-specific factors when evaluating the environmental performance of PV technologies. Solar irradiation, installation angle and local environment characteristics play a crucial role in determining the environmental impacts and energy efficiency of PV systems. In this sense, an exhaustive study must be carried out considering the site conditions before installing PV systems, emphasizing the need to adapt installation strategies to the specific conditions of each site to maximize environmental and energy benefits.

5.2.2 By time horizons

Figure 5.8 shows the results of the comparative LCA, showing environmental impacts across the different technologies and time horizons. The analysis has revealed similar trends across the three technologies, although notable differences have been observed between utility-scale technologies (floating and bifacial PV) and the small-scale BIPV technology. Across all technologies, there has been a clear pattern of decreasing environmental impacts from 2022 to 2050, with the largest impacts observed in 2022 and the smallest in 2050.

The analysis has indicated that utility-scale technologies (floating and bifacial) generally have steeper reductions in environmental impacts compared to small-scale technology (BIPV). For utility-scale technologies, the impacts on IR and ADe have been higher for 2030 scenario, mainly due to differences in cell types and their manufacturing processes, as well as different system efficiencies.

Efficiency improvements, especially in innovative technologies such as perovskite cells, have played a critical role in reducing environmental impact. Perovskite cells demonstrated 7% higher efficiency compared to TOPCON cells. This leaded to a decrease in material and infrastructure requirements over time. For example, the need for infrastructure has decreased by approximately 20% between 2030 and 2050 due to better performance. On the other hand, the differences between 2022 and 2030 have not been only in terms of performance, which for 2030 is around 3% higher than for 2022, but also the lifespan has been considered to increase by 10 years for 2030 and 2050. According to data, for the production 1kWh, 32% less infrastructure has been needed for 2030 compared to 2022. Regarding the differences between 2022 and 2050, a decrease in infrastructure has been observed with 47%.

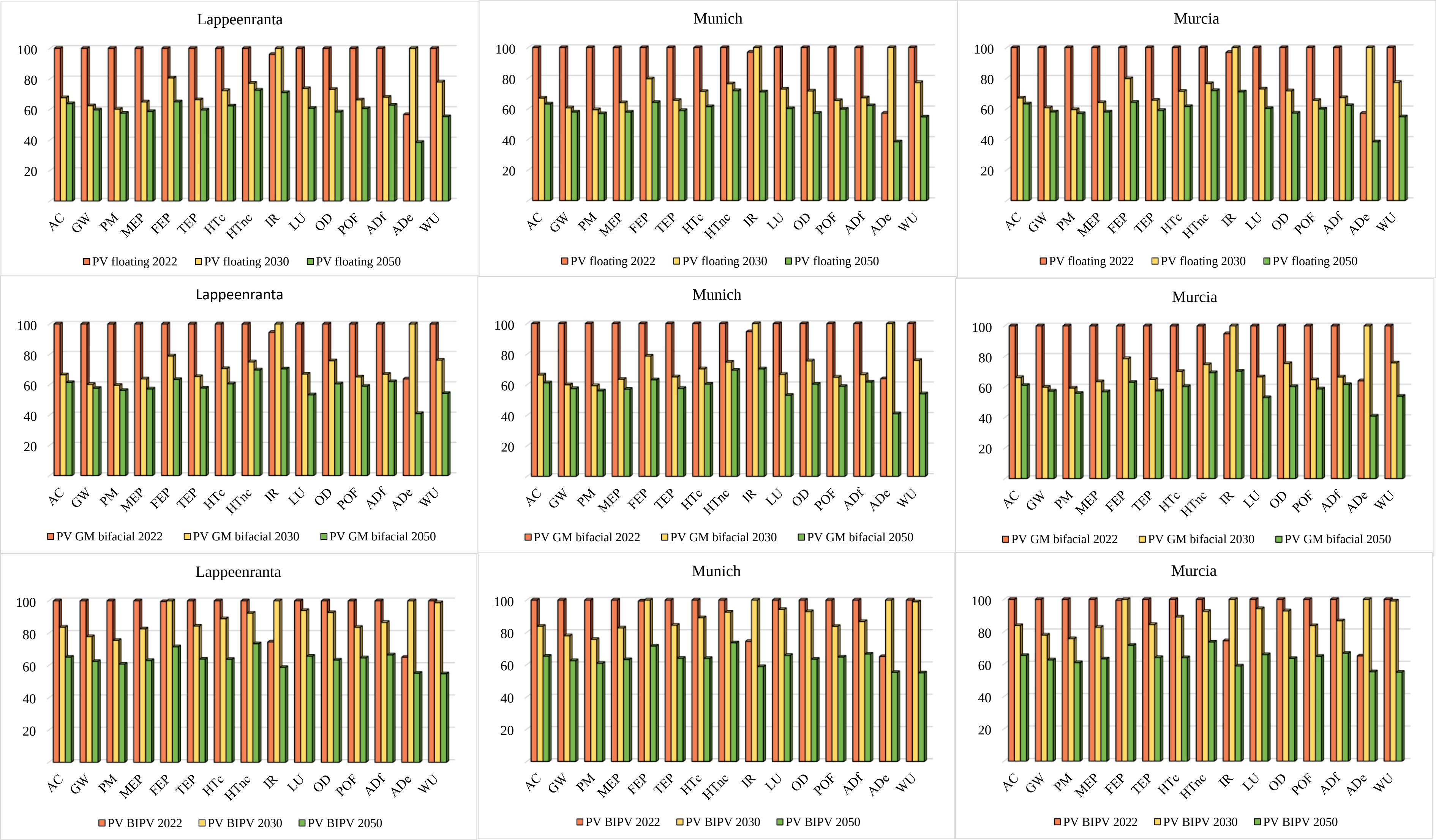


Figure 5.8: Comparative LCA of floating PV, bifacial, and BIPV technologies across varied time horizons

BIPV technology showed a slightly different trend, with higher impacts observed in 2030 compared to other time horizons in FEP, IR and ADe. This could be attributed to higher efficiency and longer plant lifespan, as in the case of utility-scale technologies. These differences have been translated into reduced consumption of raw materials and electricity per kWh generated. For example, in the case of BIPV, the efficiency of perovskite has been only 5.6% higher than in the case of TOPCON and 8.1% higher than that of PERC, and the lifespan has been estimated at 40 years for 2022 and 2030 and 50 years for 2050. In this case, increasing performance and lifespan have reduced the need for infrastructure by 39% from 2030 to 2050 and only 14% between 2022 and 2030.

The results have shown that in the case of floating technology, the impact could decrease by 23% from 2022 to 2050, 14% from 2022 to 2050 and 36% from 2022 to 2050. However, in the case of bifacial technology, the impact has decreased by 25% from 2022 to 2050, 14% from 2022 to 2050 and 38% from 2022 to 2050. Finally, in the case of BIPV technology, the impact could decrease by 6% from 2022 to 2030, 26% from 2030 to 2050 and 32% from 2022 to 2050. This trend has been independent of the geographical area considered.

In summary, the LCA analysis results have highlighted the potential of floating, bifacial, and BIPV technologies to contribute positively to environmental sustainability goals over time. The observed reductions in environmental impacts have reflected the cell efficiency and lifespan improvements, leading to lower material and energy consumption per kWh generated and reduced infrastructure needs. These findings support the adoption of these innovative PV technologies as part of efforts to mitigate environmental impacts associated with electricity generation.

5.2.3 By technology

Figure 5.9 presents a comprehensive comparative evaluation of the environmental impacts of three utility-scale PV systems, covering their entire life cycles. The systems evaluated include floating, bifacial and monofacial systems (conventional), implemented in Lappeenranta, Munich, and Murcia for the time horizons 2022, 2030, and 2050. The results shown refer to the production of 1 kWh of electricity. The analysis has considered the impacts of material extraction on system dismantling and recycling. **Table S.1, Table S.2, Table S.3, Table S.5, Table S.6, Table S.7, Table S.9, Table S.10 and Table S.11** show the characterized results of the environmental impacts of the technologies.

The comparative evaluation has revealed that the bifacial PV system generally exhibits the lowest environmental impact across most categories. The floating PV system has followed, and the monofacial PV system consistently has shown the highest impacts.

The unique ability of bifacial systems to capture sunlight from both sides of the panel not only increases energy production compared to traditional monofacial systems, but also reduces the overall environmental footprint per unit of electricity produced. This makes it a superior option for sustainable energy generation, minimizing environmental damage and maximizing efficiency.

The floating PV system has been the second to exhibit lower environmental impacts than the monofacial PV system. The main environmental benefit of the floating PV system lies in its lower land use requirements. By using bodies of water instead of land, competition for land resources can be minimized and may be particularly advantageous in regions with limited available land. The floating PV system also benefits from its unique mounting system, which differs from traditional ground-mounted PV systems and contributes to its environmental advantages.

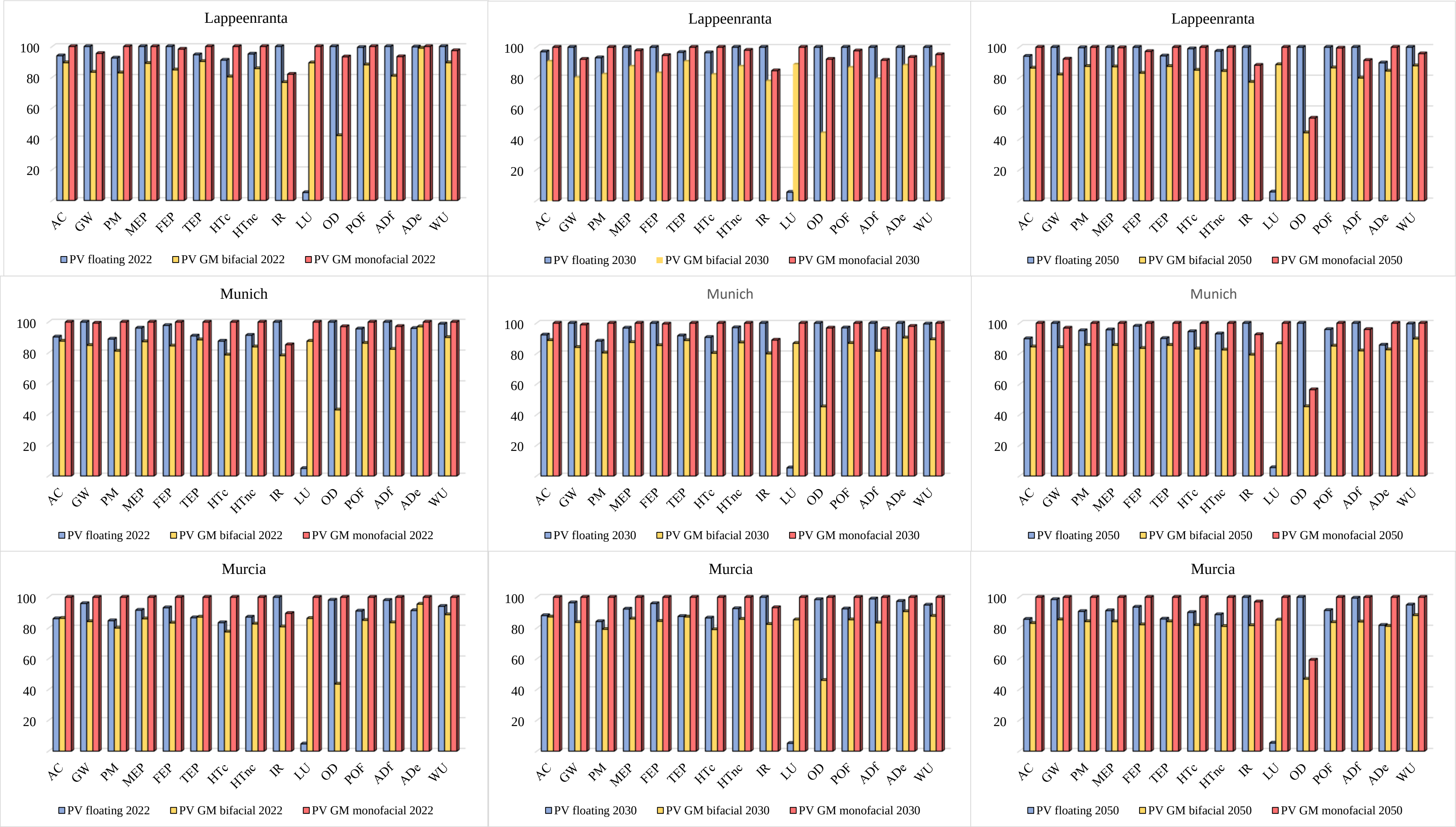


Figure 5.9: Comparative LCA of utility-scale PV systems: Floating PV, Bifacial ground-mounted, and Monofacial ground-mounted in Lappeenranta, Munich, and Murcia (2022, 2030 and 2050)

However, the analysis has also highlighted regional variations in environmental impact. In Lappeenranta, for example, excluding LU, the floating PV system has shown higher environmental impacts for all three-time horizons than the bifacial and monofacial PV systems. Furthermore, it has been observed that even for the other climatic zones, the floating system have had the most significant impact in some categories, particularly in categories such as GW, IR, OD and ADf. These results suggest that while floating PV systems may be beneficial in terms of LU, they may significantly impact other environmental categories, depending on the region and local conditions.

Conversely, the floating PV system in Murcia has exhibited lower overall environmental impacts than Lappeenranta and Munich. This could be attributed to the region's higher solar radiation levels [40], which enhance the energy production efficiency of PV systems and thus reduce their environmental impacts per unit of energy generated. The floating PV system also benefits from its unique mounting system, which differs from traditional ground-mounted PV systems and contributes to its environmental advantages.

The results have shown that although the variations in environmental impact between the utility-scale PV systems evaluated have been relatively minor, the study has highlighted the sustainability benefits of new PV technologies, particularly bifacial and floating systems, compared to conventional systems, monofacials [45–48]. These results could implode the implementation of utility-scale PV systems, highlighting the importance of integrating innovative technologies.

Figure 5.10 presents a comprehensive assessment of the environmental impacts of two small-scale PV systems over their entire life cycle. The BIPV (innovative system) and the BAPV (conventional system) implemented in Lappeenranta, Munich and Murcia for the time horizons 2022, 2030 and 2050 have been compared. **Table S.12, Table S.13, Table S.14, Table S.16, Table S.17 and Table S.18** show the characterized results of the environmental impacts of the technologies.

The evaluation has revealed that the innovative system (BIPV) has presented the most significant environmental impact in all scenarios, regardless of the time horizon or climatic location. This system has shown a more significant impact in most categories, except PM and HTc, in the Lappeenranta scenarios for 2022 and 2050. The higher environmental performance of the BIPV system could be attributed to the installation angle of the systems, which affects the amount of energy produced. BIPVs have had a 90° installation angle, while BAPVs have had a 35° angle, which has reduced the annual inclined global solar radiation by 25% to 35%, resulting in lower energy production.

To reduce the impact of BIPV systems, it is recommended to optimize their installation angle to maximize solar gain, especially in areas with less solar exposure [49,50]. Installing BIPV on inclined rooftops with angles between 30° and 45° instead of façades could increase the capture of direct solar radiation. It could also be installed on flat rooftops, but adjusting the angle according to the latitude and climatic conditions of the place where it is installed. It is crucial to promote BIPV designs that improve the energy efficiency of buildings and their integration into dense urban environments [51,52]. Integration BIPV into structural elements such as pergolas and windows could offer additional benefits in solar capture and energy efficiency [53,54]. It is also recommended that more sustainable materials for BIPV systems be developed.

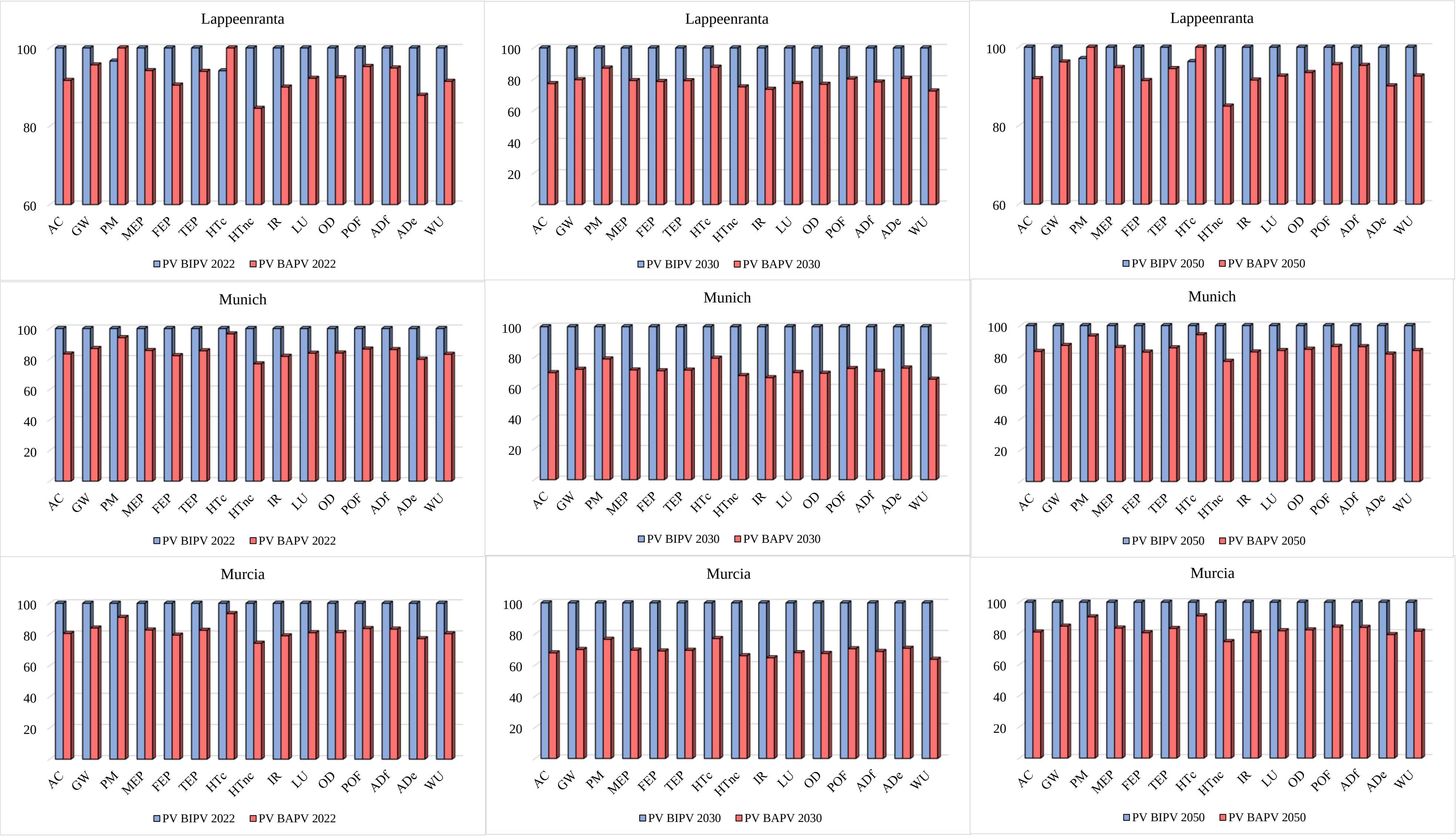


Figure 5.10: Comparative LCA of small-scale PV systems: BIPV and BAPV in Lappeenranta, Munich, and Murcia (2022, 2030 and 2050)

5.3 Penetration of solar photovoltaics into the power grid

This analysis aimed to determine the environmental performance associated with integrating various PV systems (floating, bifacial, monofacial, BIPV, and BAPV) into the power grid systems of Finland, Germany, and Spain for the years 2022, 2030, and 2050. The objective has been to assess how integrating these systems in the grid could influence environmental impacts over different temporal perspectives. It should be noted that for this analysis only the technological improvements planned in the solar sector have been included, but not those corresponding to the other energy sectors (renewable or non-renewable). Considering this, if the expected improvements in all energy sectors were taken into account, an even greater reduction in environmental impact would be expected.

Table 5.1, **Table 5.2** and **Table 5.3** present the proportions of different energy sources (renewable and non-renewable) considered for Finland, Germany, and Spain for the respective time horizons of 2022, 2030, and 2050. This data has formed the basis for a comprehensive evaluation that provides insights into the potential environmental benefits and challenges associated with the adoption of advanced PV technologies in diverse geographical and temporal contexts.

Table 5.1: Finnish power grid: perspectives for 2022, 2030, and 2050 [55–57]

Energy source	2020	2030	2050
Hydropower	19.70%	12.10%	6.60%
Wind power	9.00%	54.50%	53.30%
Wood fuel	12.00%	2.00%	2.80%
Solar PV (total)	0.10%	5.20%	29.50%
BAPV	0.10%	1.50%	4.50%
BIPV	-	0.10%	0.20%
Ground mounted monofacial	-	1.80%	3.00%
Ground mounted bifacial	-	1.70%	21.30%
floating	-	0.10%	0.50%
Biogas	0.60%	2.80%	2.50%
Coal	5.50%	-	-
Natural gas	4.70%	0.20%	0.10%
Nuclear	25.00%	23.20%	5.20%
Imported (Total)	26.10%		
Imported (SE)	20.00%		
Imported (RU)	3.10%		
Imported (NO)	0.30%		
TOTAL	***100%***	***100%***	***100%***

Table 5.2: German power grid: perspectives for 2022, 2030, and 2050 ([58,59])

Energy source	2022	2030	2050
Lignite coal	18.61%	-	-
Hard coal	10.28%	7.80%	-
Nuclear	5.49%	-	-
Natural gas	12.73%	3.50%	-
Mineral oil	0.70%	-	-
Wind power	19.99%	66.10%	43.70%
Hydropower	2.79%	1.30%	0.80%
Wood fuel	7.12%	0.80%	0.50%
Solar PV (total)	9.70%	19.70%	54.50%
BAPV	6.90%	9.30%	13.20%
BIPV	0.10%	0.20%	0.30%
Ground mounted monofacial	2.60%	4.50%	4.00%
Ground mounted bifacial		5.50%	36.50%
floating	0.10%	0.20%	0.50%
Waste	0.89%	0.70%	0.40%
Geothermal	0.03%	0.10%	0.10%
Biogas	3.80%	-	-
Import (total)	7.78%		
Import France	1.30%	-	-
Import Czechia	1.24%	-	-
Import Denmark	1.20%	-	-
Import Netherlands	1.00%	-	-
Import Switzerland	0.98%	-	-
Import Austria	0.80%	-	-
Import Norway	0.48%	-	-
Import Belgium	0.29%	-	-
Import Sweden	0.28%	-	-
Import Italy	0.28%	-	-
Import Poland	0.04%	-	-
TOTAL	***100%***	***100%***	***100%***

Table 5.3: Spanish power grid: perspectives for 2022, 2030, and 2050 ([58,60])

Energy source	2022	2030	2050
Hydropower	6.41%	7.00%	5.00%
Wind power	22.21%	31.10%	30.10%
Solar PV (total)	10.00%	39.00%	63.20%
BAPV	4.80%	6.10%	10.10%
BIPV	0.10%	0.20%	0.30%
Ground mounted monofacial	4.90%	14.70%	4.50%
Ground mounted bifacial	0.10%	17.50%	47.60%
floating	0.10%	0.50%	0.70%
Solar thermal	1.48%	0.90%	-
Solar tower	1.67%	0.70%	1.40%
Nuclear	20.24%	6.30%	-
Natural gas	24.06%	11.60%	-
Coal	2.79%	1.90%	-
Mineral oil	0.91%	-	-
Biogas	6.67%	1.00%	-
Waste	0.68%	0.50%	0.30%
Import (total)	2.88%	-	-
Import France	1.63%	-	-
Import Portugal	1.10%	-	-
Import Morocco	0.15%	-	-
TOTAL	***100%***	***100%***	***100%***

Figure 5.11 shows the projected changes in the environmental impact associated with Finland's power grid for 2022, 2030, and 2050. **Table S.19** shows the characterized values of the environmental impacts of the penetration of solar PV into the Finland power grid. For 2022, the majority of the impact categories has shown a contribution of 100%, indicating that the environmental impact of the power grid has been significantly higher compared to 2030 and 2050. Notably, the average impact for 2030 has been about 49%, further reducing to 45% in 2050. This reduction could be attributed to the anticipated changes in energy sources over time.

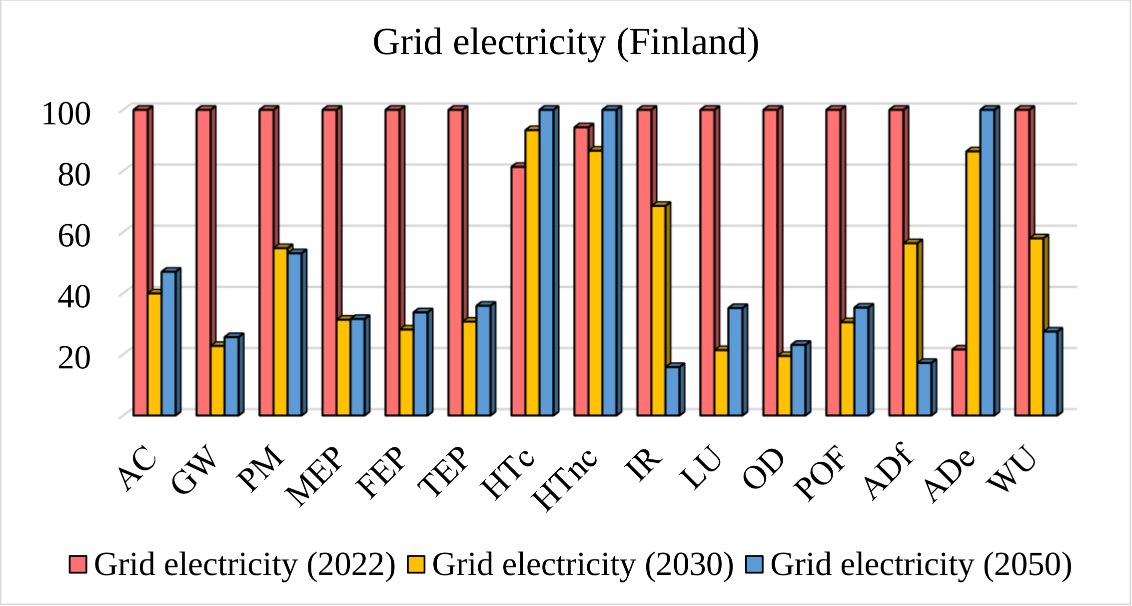


Figure 5.11: Projected environmental impact of Finland's power grid for 2022, 2030, and 2050

For instance, non-renewable energy sources have been estimated to decrease substantially from 41% in 2022 to 23% in 2030 and 5% in 2050. In 2022, energy imports have a considerable impact (18%). Although the highest proportion of electricity imports come from Sweden (20%), the environmental impact associated with these imports has been 9%. In comparison, the impact of Russian imports has been 8%, even though they only constitute 3.1% of the total electric grid. The main contributors to the environmental impact in 2022 have been energy production from wood (30%), coal (17%), and nuclear power (15%). Wood has had a high impact in several impact categories, including AC, PM, MEP, TEP, HTc, HTnc, LU, and POF. Coal has affected GW and FEP, while nuclear power impacts IR, ADf, and WU. Additionally, as seen in **Table 5.1**, the contribution of PV systems to the grid has been minimal at 0.1% for BIPV, resulting in an average impact of just 0.13%. Some categories have shown notable changes in 2022, particularly HTc, HTnc, and ADe, which indicate the lowest impact for this scenario. This could be associated with an increase in the proportion of wind energy.

In the 2030 scenario, the environmental impact has been reduced by more than 50% compared to 2022 (as shown in **Table S.19**). The major energy sources contributing to the impact in 2030 have been nuclear power (averaging 25%), wood (15%), and wind energy (40%). Nuclear power significantly impacts IR, ADF, and WU, while wood has affected MEP, TEP, LU, and OD. The increase in the environmental impact associated with wind energy has been due to its projected rise to over 40% of the total energy mix, while the proportion of nuclear power has been estimated to decrease by 2% from 2022 to 2030. The increasing share of wind energy in the grid results in this type of energy becoming the primary contributor to the other impact categories. Additionally, as shown in **Table 5.1**, the contribution of PV systems to the grid has increased from 0.1% in 2022 to 5.2% in 2030, resulting in an average impact of 5.3%.

Finally, the 2050 scenario has shown the lowest overall environmental impact. The primary contributors in 2050 have been nuclear power (15%), wind energy (36%), wood (17%), and solar PV (20%). In terms of environmental impact, nuclear power has had a significant effect on IR (96%), ADF (68%), and WU (37%). Wind energy has impacted AC (40%), GW (38%), PM (38%), MEP (33%), FEP (55%), HTc (69%), HTnc (64%), POF (37%), and ADe (67%). Wood energy has shown the highest contribution to TEP (38%), LU (61%), and OD (31%). The increase in the impact of solar PV has been due to its higher penetration in the energy mix, rising from 5.2% in 2030 to an estimated 29.5% in 2050.

Figure 5.12 and **Table** S.20 presents the projected changes in the environmental impact of Germany's power grid for 2022, 2030, and 2050. In 2022, most impact categories have been at 100%, except for ADe. By 2030, the average impact has dropped to 40%; by 2050, it has further decreased to 25%, reflecting anticipated shifts in energy sources over time.

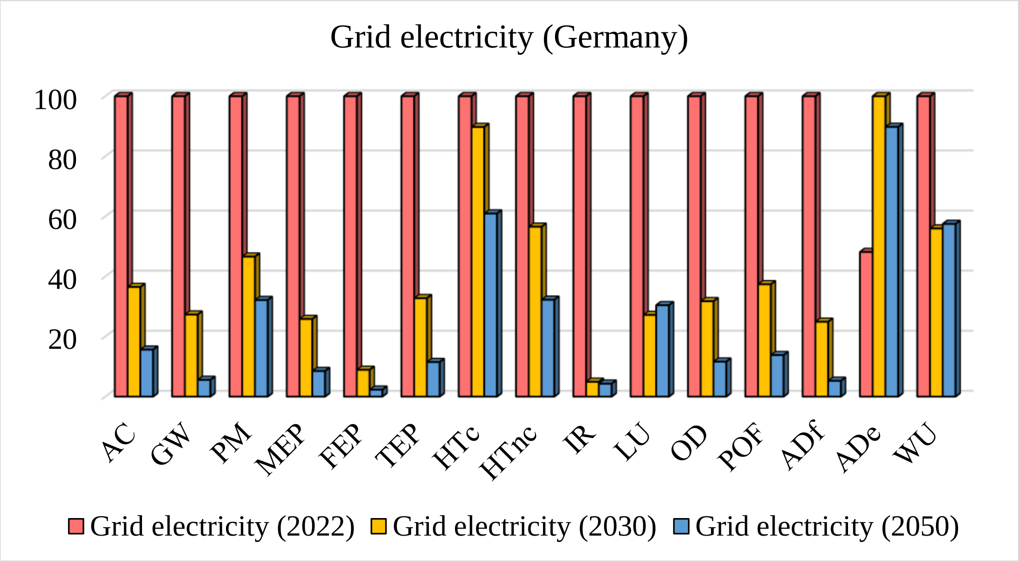


Figure 5.12: Projected environmental impact of Germany's power grid for 2022, 2030, and 2050

It has been estimated that the use of non-renewable energy drops significantly from 56% in 2022 to 11% in 2030, with the use of non-renewable energy being eliminated in 2050. In 2022, energy imports accounted for 7.87% of the impact, but no imports have been assumed for 2030 and 2050. The main contributors to the environmental impact in 2022 have been lignite (27%), coal (16%), and wood (15%). Lignite has had the highest contribution in 10 out of 15 impact categories. Wood significantly affects 2 impact categories: PM, with a contribution of 35% and LU, with a contribution of 84% of this impact categories. On average, carbon has had high relative impacts but has not had the highest contribution in any impact categories. PV systems have contributed 9.7% to the grid, with an average impact of 6.3%. The relatively low impact for ADe in 2022 has been likely due to increased installations of wind and solar plants for 2030 and 2050.

By 2030, the environmental impact has been reduced by 60% compared to 2022. The main sources of impact have been the use of coal (37%), wind (28%), and solar PV (17%). The results have shown that non-renewable energy (coal) affects the majority of environmental categories (AC, GW, MEP, FEP, TEP, HTnc, POF, and ADe) with impacts ranging from 36% (HTnc) to 60% (FEP). On the other hand, renewable energy sources have had the highest impacts in 5 categories: wind energy leads in 2 categories (PM with an impact of 48% and HTc with an impact of 70%), and solar PV leads in 3 categories (IR - 33%, ADe - 54%, and WU - 42%). In 2022, wind energy has been assumed to be 20% and solar PV 9.7% of the energy mix. By 2030, wind energy has been estimated to increase to 66.1%, while solar PV has been estimated to rise to 19.7%.

By 2050, the overall environmental impact has been the lowest: 25%. Wind energy (35%) and solar (54%) have contributed most. In this scenario, solar PV has led in the following impact categories: AC (55%), GW (52%), MEP (48%), FEP (34%), TEP (47%), HTnc (50%), IT (50%), LU (64%), OD (61%), POF (46%), ADf (56%), ADe (68%), and WU (45%). Notably, among solar PV technologies, bifacial panels have contributed the most and had the highest share in the grid. The impact of solar PV has increased due to its rise from 19.7% in 2030 to 54.5% in 2050. On the other hand, wind energy has had the highest impact in only 2 categories: PM (47%) and HTc (68%). The integration of wind energy in the grid has been estimated to be 66.1% in 2030, and decreasing to 43.7% in 2050.

The environmental impacts of the Spanish power grid, based on the 2022 composition and making predictions for 2030 and 2050, are detailed in **Figure 5.13** and **Table S.21**. These projections have shown a significant reduction in environmental impacts, driven by a change towards renewable energy sources and a corresponding decrease in the use of non-renewable sources.

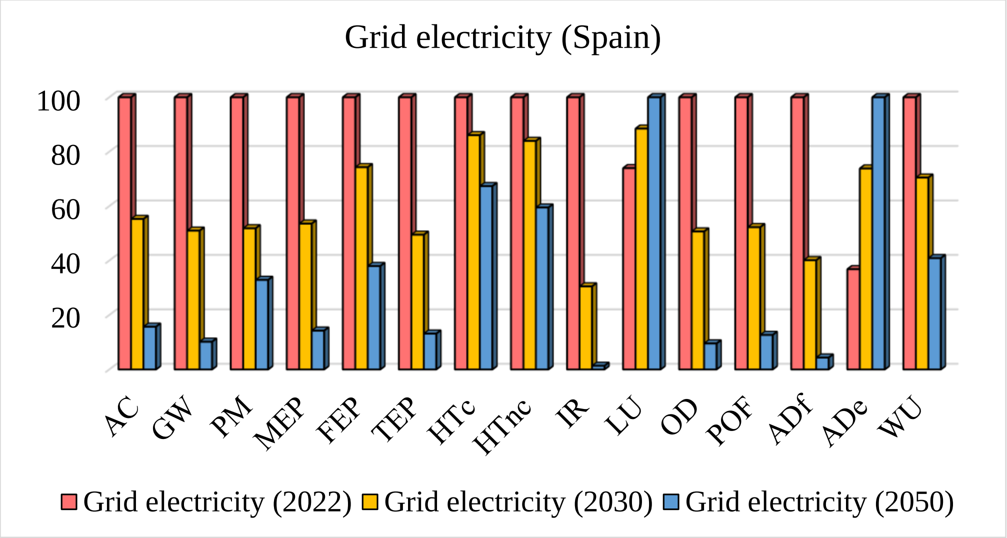


Figure 5.13: Projected environmental impact of Spain's power grid for 2022, 2030, and 2050

In 2022, the energy mix in Spain has been assumed to comprise 49.1% renewable sources and 50.9% non-renewable sources, with imports representing 2.9%, nuclear power 20% and natural gas 24%. By 2030, the share of renewable energy has been estimated to increase dramatically to 70.2%, leaving only 19.8% non-renewable sources. By 2050, all energy has been estimated to come from renewable sources. It has been anticipated that the predominant renewable sources in 2050 could be PV and wind energy.

The scenario for 2022 has shown the highest environmental impact in almost all categories, with an average total impact of 94%. This year, 13 of 15 categories have shown the most significant impact. However, in the LU and ADe categories, the 2022 scenario has had the lowest impact, with 74% and 37%, respectively. This has been attributed to the lower penetration of PV systems in 2022, only 13.1%, compared to 40.6% in 2030 and 64.6% in 2050. The increased installation of PV systems, particularly bifacial, in the years 2030 and 2050 could require more land and materials, generating higher impacts in the LU and ADe categories.

Electricity production from natural gas, coal, and nuclear power have been the main contributors to environmental impacts in 2022. For example, natural gas has been responsible for 85% of the OD and 62% of the GW categories' total impact. Coal has contributed 46% of the total impact in the AC category and 56% in the FEP category. Nuclear power has had a significant impact in the IR category, with 94% and 48% in the ADf category.

By 2030, the environmental impact has been decreased by 33% compared to 2022. The shift towards renewable energy sources continues, and the environmental impact of this scenario decreases. Still, even so, the use of natural gas, coal and nuclear power have remained mainly responsible for the impact of this scenario. On the other hand, solar PV has been beginning to play a more prominent role, which has implied an increase, with an average impact of 18% among the various technologies. In this scenario, solar PV has had a notable impact in the PM category, with 26% and 70% in the ADe category.

The scenario for 2050 has shown the lowest global environmental impact, with a reduction of 59% compared to 2022. The main contributors to this year's environmental impact have been wind energy, specifically "wind, 1-3 MW turbine, onshore " (13%), and solar PV, especially bifacial (38%) and BAPV (12%). In this scenario, the installation of bifacial systems, which has been estimated to represent 47.6% of the total power grid in 2050, has generated the highest impact in 12 of the 15 categories. Furthermore, installing solar technologies together has generated a total impact on LU of 47%. Wind energy primarily has affected the HTc category, with all wind technologies contributing 47% of the impact in this category. Finally, the WC category has been predominantly affected by hydropower production, which represents 77% of the impact in this category.

Based on the projected changes in the environmental impact of the power grids in Finland, Germany, and Spain for the years 2022, 2030, and 2050, it has been evident that transitioning to renewable energy sources is crucial for reducing environmental impacts. Significant reductions in non-renewable energy use are expected in all three countries, leading to a marked decrease in overall environmental impact. For Finland, the shift from non-renewable sources like coal and wood towards wind and solar PV will substantially reduce impact by 2050. Similarly, Germany's move away from lignite and coal to wind and solar PV is projected to lower the environmental impact by 2050, with solar PV playing a particularly prominent role. Spain's energy mix shows the most dramatic change, with an almost complete transition to renewable sources by 2050, dominated by PV and wind energy, resulting in the lowest environmental impact.

To achieve the transition to renewable energy, governments and stakeholders must invest in developing and installing renewable energy projects. Furthermore, improving energy efficiency in all sectors and promoting technological innovation in renewable energy are necessary actions to reduce environmental impacts further. It is essential to implement policies that incentivize the adoption of renewable energy and gradually eliminate subsidies for non-renewable energy sources. Finally, it is crucial to increase public awareness of the benefits of renewable energy and encourage community participation in sustainable energy transition initiatives.

5.4 Key sustainability indicators

Key Sustainability Indicators (KSI) are measures used to assess the environmental and socio-economic performance of PV (PV) systems, focusing on critical aspects such as resource efficiency, GHGs, and sustainability throughout their lifecycle. These indicators are essential for understanding and comparing the environmental and economic impact of different PV technologies and system configurations. However, in this study, the focus has been exclusively on the environmental aspects of PV systems, using these KSI to measure and compare the environmental performance of different PV technologies and configurations.

For PV systems, especially bifacial, floating, monofacial, BIPV and BAPV, the following KSI have been selected for analysis:

- **Environmental footprint**: This indicator calculates the overall environmental footprint by considering the single weighting of LCA results using the PEF method. It provides a comprehensive measure of the PV system's environmental impact.
- **GHG emissions from energy production**: This indicator is derived from LCA, using the GW category included in the PEF method. It measures direct and indirect greenhouse gas emissions associated with energy production throughout the PV system's lifecycle.
- **Waste generation to units of energy produced**: This indicator is derived from the LCA using the EDIP method. This method considers hazardous waste, slags/ashes, bulk, and radioactive waste. This method evaluates the amount of solid waste generated during the entire life cycle of the PV systems, normalized by the amount of energy produced. It aims to minimize waste generation and improve waste management practices.
- **Water footprint**: Derived from LCA, using the WU category included in the AWARE method. This indicator assesses direct and indirect water consumption associated with the PV system's lifecycle, from production to end-of-life.
- **Land use**: Derived from the LCA, using the Land Occupation category included in the Selected LCI Results method, this indicator analyses the land required for installing and operating the PV system. It evaluates land use efficiency and its environmental implications.
- **The ratio between renewable and non-renewable energy in the power grid**: This indicator evaluates the proportion of renewable energy generated by the PV system compared to non-renewable energy used for production and operation.

These KSI have been evaluated for the three-time horizons (2022, 2030, and 2050) and in the three different climatic zones (Finland, Germany, and Spain). This allows for understanding how the environmental impacts of PV systems vary under various climatic conditions and different time horizons.

Table 5.4 presents the environmental footprint of the PV technologies (floating, bifacial, monofacial, BIPV and BAPV) analysed in this work in three countries (Finland, Germany and Spain) and three-time horizons (2022, 2030 and 2050).

Table 5.4: Evolution of the KSI: environmental footprint of the five solar technologies in three European countries (2022-2050)

Environmental footprint (µPt(kWh)				
Year	**PV technology**	**Finland**	**Germany**	**Spain**
2022	Floating	7.08	5.46	3.69
	Bifacial	6.72	5.28	3.69
	Monofacial	7.42	5.95	4.23
	BIPV	11.82	10.54	7.66
	BAPV	10.80	8.75	6.15
2030	Floating	7.06	5.40	3.66
	Bifacial	6.35	4.98	3.47
	Monofacial	6.98	5.60	3.97
	BIPV	14.02	12.52	9.09
	BAPV	11.21	9.07	6.39
2050	Floating	4.46	3.41	2.31
	Bifacial	4.08	3.20	2.23
	Monofacial	4.72	3.78	2.69
	BIPV	8.80	7.86	5.71
	BAPV	8.12	6.57	6.39

The results have shown that a solar PV system installation in Spain has had a lower environmental footprint in all PV technologies and time horizons, due to favourable climatic conditions and greater solar irradiance, which generates greater production of electrical energy.

In addition, floating and bifacial PV technologies have had a smaller environmental footprint than monofacial, BIPV and BAPV, making them more environmentally sustainable options. BIPV has had the highest environmental footprint, indicating that the integration of PV energy in buildings should be improved mainly in terms of efficiency, considering the installation at different angles that would allow a higher capture of saline radiation and, thus, higher electricity production.

Table 5.5 presents the KSI related to GHGs from energy production, measured in kg of CO_2 equivalent, for the five PV technologies in Finland, Germany, and Spain over three-time horizons: 2022, 2030 and 2050.

Table 5.5: Evolution of the KSI: GHG emissions of the five solar technologies in three European countries (2022-2050)

GHG emissions from energy production (kg CO2 eq/kWh)				
Year	**PV technology**	**Finland**	**Germany**	**Spain**
2022	Floating	5.67E-02	4.37E-02	2.96E-02
	Bifacial	4.72E-02	3.71E-02	2.60E-02
	Monofacial	5.41E-02	4.34E-02	3.08E-02
	BIPV	6.88E-02	6.14E-02	4.46E-02
	BAPV	6.58E-02	5.33E-02	3.75E-02
2030	Floating	3.45E-02	2.64E-02	1.79E-02
	Bifacial	2.84E-02	2.22E-02	1.55E-02
	Monofacial	3.26E-02	2.62E-02	1.86E-02
	BIPV	5.35E-02	4.78E-02	3.47E-02
	BAPV	4.26E-02	3.45E-02	2.43E-02
2050	Floating	3.31E-02	2.54E-02	1.72E-02
	Bifacial	2.72E-02	2.13E-02	1.49E-02
	Monofacial	3.06E-02	2.45E-02	1.74E-02
	BIPV	4.29E-02	3.83E-02	2.79E-02
	BAPV	4.13E-02	3.35E-02	2.36E-02

In 2022, Spain has shown the lowest GHG emissions across all technologies, with floating PV emitting 2.96E-02 kg CO_2 eq, bifacial PV 2.60E-02 kg CO_2 eq, and monofacial PV 3.08E-02 kg CO_2 eq. BIPV has recorded the highest emissions with 4.46E-02 kg CO_2 eq. Germany and Finland have had higher emissions in all technologies, with Finland emitting the most in BIPV with 6.88E-02 kg CO_2 eq.

By 2030, emissions have decreased in all countries. Spain has had the lowest emissions, with floating PV at 1.79E-02 kg CO_2 eq and bifacial PV at 1.55E-02 kg CO_2 eq. BIPV has shown an increase in emissions compared to 2022, reaching 5.35E-02 kg CO_2 eq in Finland. However, the other technologies have continued to show a reduction in emissions.

In 2050, a significant decrease in GHG emissions has been observed across all technologies and countries. Spain has continued to lead with the lowest emissions, showing floating PV with 1.72E-02 kg CO_2 eq and bifacial PV with 1.49E-02 kg CO_2 eq. BIPV has continued to have the highest emissions, although they have had decreased, with 2.79E-02 kg CO_2 eq in Spain.

In this sense, the results have shown that Spain consistently presents the lowest GHG emissions in all technologies and time horizons due to its high solar irradiance and greater energy production. Floating and bifacial PV technologies have shown lower emissions compared to monofacial, BIPV and BAPV, standing out as more environmentally sustainable options. BIPV has had the highest emissions, indicating that it requires optimizations in energy efficiency and materials used. The general trend has reflected a decrease in GHG emissions from 2022 to 2050, indicating technological advances and higher efficiency.

Table 5.6 displays the KSI related to the solid waste generated per 1kWh of energy produced by floating, bifacial, monofacial, BIPV, and BAPV technologies installed in Finland, Germany, and Spain across three-time horizon (2022, 2030, and 2050). This indicator is calculated using the EDIP method, which considers hazardous waste, slags/ashes, bulk waste, and radioactive waste throughout the PV system's lifecycle.

Table 5.6: Evolution of the KSI: waste generation for the five solar technologies in three European countries (2022-2050)

Waste generation to units of energy produced (kg/kWh)				
Year	**PV technology**	**Finland**	**Germany**	**Spain**
2022	Floating	1.10E-02	8.52E-03	5.76E-03
	Bifacial	9.66E-03	7.59E-03	5.31E-03
	Monofacial	1.03E-02	8.27E-03	5.87E-03
	BIPV	1.08E-02	9.68E-03	7.03E-03
	BAPV	1.05E-02	8.48E-03	5.96E-03
2030	Floating	7.02E-03	5.37E-03	3.64E-03
	Bifacial	6.07E-03	4.76E-03	3.32E-03
	Monofacial	6.44E-03	5.17E-03	3.67E-03
	BIPV	8.47E-03	7.56E-03	5.49E-03
	BAPV	6.69E-03	5.41E-03	3.82E-03
2050	Floating	6.15E-03	4.71E-03	3.19E-03
	Bifacial	5.29E-03	4.15E-03	2.90E-03
	Monofacial	5.46E-03	4.38E-03	3.11E-03
	BIPV	6.12E-03	5.46E-03	3.97E-03
	BAPV	5.90E-03	5.41E-03	3.39E-03

In 2022, Finland, Spain, and Germany have exhibited varying rates of waste generation per unit of energy produced (kg/kWh) based on the type of PV technology. Overall, Spain has demonstrated the lowest values across all categories, followed by Germany and Finland. Bifacial and monofacial technologies have tended to produce less waste compared to the rest of the technologies.

By 2030, a trend towards the reduction of waste generation has been observed across all categories and countries. Spain and Germany have displayed the lowest rates, particularly in bifacial and monofacial technologies, while Finland has significantly reduced its results.

By 2050, waste generation rates have continued to decline, reflecting improvements in the efficiency and sustainability of PV technology across all countries. Spain has maintained its lead in terms of energy production with the least waste generation, closely followed by Germany and Finland. Bifacial and monofacial technologies have remained the most efficient options in waste management, while BIPV and BAPV have shown improvements but still generated more waste comparatively.

In summary, Spain has stood out for its low waste generation in PV systems due to its highly efficient energy production. Environmentally, bifacial and monofacial PV technologies have been better, generating less waste than floating, BIPV, and BAPV. BIPV. The downward trend in waste generation from 2022 to 2050 has signalled technological and efficiency progress, underscoring improvements in PV waste management.

Table 5.7 shows water use (m³) for floating, bifacial, monofacial, BIPV and BAPV technologies installed in Finland, Germany and Spain.

Table 5.7: Evolution of the KSI: water use for the five solar technologies in three European countries (2022-2050)

Water use(m³/kWh)				
Year	**PV technology**	**Finland**	**Germany**	**Spain**
2022	Floating	4.05E-02	3.12E-02	2.11E-02
	Bifacial	3.61E-02	2.83E-02	1.98E-02
	Monofacial	3.93E-02	3.15E-02	2.24E-02
	BIPV	5.00E-02	4.46E-02	3.24E-02
	BAPV	4.57E-02	3.71E-02	2.60E-02
2030	Floating	3.07E-02	2.35E-02	1.59E-02
	Bifacial	2.68E-02	2.10E-02	1.47E-02
	Monofacial	2.94E-02	2.36E-02	1.67E-02
	BIPV	4.82E-02	4.31E-02	3.13E-02
	BAPV	3.49E-02	2.83E-02	1.99E-02
2050	Floating	2.23E-02	1.70E-02	1.15E-02
	Bifacial	1.95E-02	1.53E-02	1.07E-02
	Monofacial	2.13E-02	1.71E-02	1.21E-02
	BIPV	2.73E-02	2.44E-02	3.13E-02
	BAPV	2.53E-02	2.05E-02	1.44E-02

The results have shown that, in 2022, Spain has been the scenario that uses the least water. Furthermore, floating, bifacial and monofacial technologies use the least water. Contrarily, BIPV has recorded the highest water consumption of all technologies. Germany and Finland have higher water use across all technologies.

In the case of scenarios related to 2030, it has been observed that water use has been decrease in all countries. Spain has continued to have the lowest water consumption, maintaining the trend that BIPV uses the highest amount of water compared to other technologies, reaching 3.13E-02 m³ in Germany. However, other technologies have shown a reduction in water use.

Finally, by 2050, a significant decrease in water use has been noted across all technologies and countries. Spain standing out again as the best option for the installation of the systems.

In this way, it has been observed that Spain consistently shows the lowest water use in all technologies and time horizons. Additionally, it has been observed that floating and bifacial technologies show lower water use compared to monofacial, BIPV and BAPV options, making them more environmentally friendly options. The overall trend has reflected a decrease in water use from 2022 to 2050, suggesting that technological advances help with water conservation issues.

Table 5.8 presents the land occupation for floating, bifacial, monofacial, BIPV and BAPV, deployed across Finland, Germany, and Spain at three distinct intervals: 2022, 2030, and 2050. In LCA, land use occupation is measured as area time (m^2a). It is important to clarify that the results represent not just the direct footprint of the technologies but the cumulative land usage throughout their lifecycle, encompassing the space required for ancillary activities like manufacturing materials, energy production, chemical processing, etc.

Table 5.8: Evolution of the KSI: land occupation for the five solar technologies in three European countries (2022-2050)

Land occupation (m^2a/kWh)				
Year	**PV technology**	**Finland**	**Germany**	**Spain**
2022	Floating	3.85E-03	2.97E-03	2.01E-03
	Bifacial	4.81E-03	3.78E-03	2.64E-03
	Monofacial	5.34E-03	4.29E-03	3.04E-03
	BIPV	4.21E-03	3.76E-03	2.73E-03
	BAPV	3.88E-03	3.14E-03	2.21E-03
2030	Floating	2.83E-03	2.16E-03	1.46E-03
	Bifacial	3.38E-03	2.65E-03	1.85E-03
	Monofacial	3.76E-03	3.02E-03	2.14E-03
	BIPV	3.97E-03	3.55E-03	2.58E-03
	BAPV	3.03E-03	2.45E-03	1.73E-03
2050	Floating	2.33E-03	1.78E-03	1.21E-03
	Bifacial	2.75E-03	2.16E-03	1.51E-03
	Monofacial	3.13E-03	2.51E-03	1.78E-03
	BIPV	2.74E-03	2.45E-03	1.78E-03
	BAPV	2.54E-03	2.06E-03	1.45E-03

Generally, a trend has been observed toward reducing land occupation per unit of kWh over time in all types of installations. This has reflected technological advances that increase the efficiency of solar panels, allowing higher energy production per square meter. For example, floating installations occupied between 3.85 and 2.01 m^2/kWh in 2022, reducing to 2.33 and 1.21 m^2/kWh in 2050. Bifacial, monofacial, BIPV and BAPV installations show a similar trend, with significant reductions in land occupancy by 2050. Finland has tended to have higher land occupation values than Germany and Spain, especially in bifacial, monofacial, and BIPV installations. Land reduction is crucial as it indicates greater efficiency in land use and less pressure on natural resources, signalling a sustainable development of renewable energies, especially in densely populated urban areas or areas of high ecological value.

Table 5.9 shows the evolution of the proportion between renewable and non-renewable energies in the electrical networks of Finland, Germany and Spain for 2022, 2030 and 2050.

Table 5.9: Evolution of the KSI: ratio between renewable and non-renewable energy in the Finland, Germany and Spain power grid (2022-2050)

Ratio between renewable and non-renewable energy in the power grid				
Year	**Energy type**	**Finland**	**Germany**	**Spain**
2022	Renewable	41.4%	44.3%	49.1%
	No-renewable	58.6%	55.7%	50.9%
	Ratio	0.71	0.80	0.97
2030	Renewable	76.6%	88.7%	80.2%
	No-renewable	23.4%	11.3%	19.8%
	Ratio	3.27	7.85	4.05
2050	Renewable	94.7%	100.0%	100.0%
	No-renewable	5.3%	0.0%	0.0%
	Ratio	17.87	100/0	100/0

In 2022, Finland's power grid has been estimated to comprise 41.4% electricity from renewable sources and 58.6% from non-renewable sources. This proportion has translated to a ratio of 0.71, meaning that for every unit of non-renewable energy, approximately 0.71 units of renewable energy exists in the power grid.

Germany, for its part, has been estimated to generate 44.3% of its electricity from renewable sources and 55.7% from non-renewable sources in 2022, with a ratio of 0.80. Meanwhile, Spain has been estimated to reach 49.1% renewable energy and 50.9% non-renewable, with a ratio of 0.97. These ratios indicated a higher proportion of non-renewable energy than renewable energy in all three countries in 2022.

Furthermore, with the assumptions made for 2030, Finland is expected to increase its share of renewable energy significantly to 76.6%, while non-renewable energy has been estimated to be reduced to 23.4%. This has resulted in a ratio of 3.27, indicating that Finland generates approximately 3.27 units of renewable energy for every unit of non-renewable energy.

Germany's power grid has been projected to reach 88.7% renewable energy and reduce its dependence on non-renewable sources to 11.3% by 2030, resulting in an impressive ratio of 7.85. Spain, for its part, has been expected to increase its renewable energy to 80.2%, with 19.8% non-renewable energy, resulting in a ratio of 4.05.

Looking forward to the year 2050, Finland has been estimated to have 94.7% of its electricity coming from renewable sources, reducing non-renewable energy to 5.3%, resulting in a ratio of 17.87. Germany and Spain have been considered to have even more ambitious plans, projecting to obtain 100.0% of their electricity from renewable sources by 2050, eliminating the use of non-renewable energy. This has been reflected in an infinite ratio or "100/0", meaning no non-renewable energy exists in their power grids.

This data supports a significant transition towards more sustainable energy systems and decreasing the use of non-renewable energy sources. This indicates a commitment to climate change mitigation and greater energy security, taking advantage of available natural resources more sustainably and efficiently.

The study has highlighted that solar systems in Spain have a lower value in terms of all KSI considered, followed by Germany and Finland. This could be related to Spain's more favourable climatic conditions and the high solar irradiance compared to other countries. It has also been observed that, in general terms, floating and bifacial technologies have been identified as more sustainable options compared to other technologies. Regarding the results considering the three-time horizons, a clear trend of decreasing general impacts has been observed over time, obtaining the lowest values in all KSIs for 2050. Finally, the projections for 2030 and 2050 have shown significant increases in the share of renewable energy in Finland, Germany and Spain, underscoring progress towards sustainable energy goals. Overall, the study emphasizes the fundamental role of solar PV in the sustainable energy transition of the three countries, with continuous opportunities for improvement through technological innovation and integration practices.

5.5 Influence of project innovations: Performance ratio

In addition to the exhaustive hotspot environmental analyses and the different comparative analyses, a sensitivity analysis has been carried out to evaluate how the innovations developed in the project could influence the environmental performance of the PV systems. First, the critical parameters that could directly affect environmental performance and those susceptible to being modified by technological innovations have been identified. The "performance ratio (PR)" stood out as the most influential within these parameters.

However, due to the inherent complexity and time needed to fully evaluate these technological improvements, determining an exact improvement value has not been possible. Consequently, a sensitivity analysis has been carried out. The bifacial technology installed in Murcia in 2022 has been taken as the base scenario. From this reference point, several scenarios have been established, increasing the PR in increments of 0.5%, 1%, 2% and 3 %. **Figure 5.14** and **Table S.22** presents the results of this sensitivity analysis, showing how each increase in the PR influences the environmental performance of the bifacial technology.

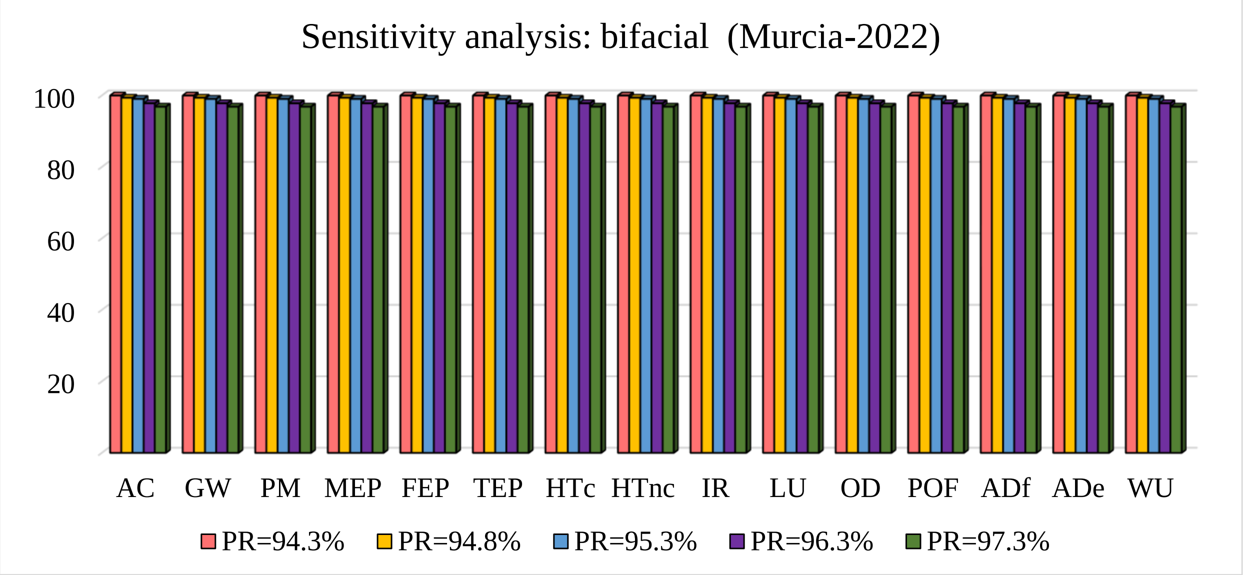


Figure 5.14: Impact of performance ratio on environmental indicators for bifacial PV systems in Murcia (2022)

The increases in PR have reflected a theoretical improvement in efficiency and an increase in annual energy production (**Table 5.10**). The system performance, measured in MWh/MWp, has also shown continuous improvement with increasing PR. Starting from a value of 2076 MWh/MWp with a PR of 94.3%, the performance has been assumed to increase to 2142 MWh/MWp with a PR of 97.3%. This increase in performance has reflected increased system efficiency and better utilization of available resources, which is crucial in the planning and development of utility-scale solar plants.

The total amount of energy produced has also shown a positive trend, increasing from 3,114,501 MWh to 3,213,584 MWh, while the PR has increased from 94.3% to 97.3%. This increase in total energy production is particularly relevant in the context of the transition towards renewable energy sources, as it contributes to reducing dependence on fossil fuels and mitigating climate change.

It is important to note that the installed and used surfaces have remained constant at 234,741 m² and 485,672 m², respectively, highlighting that the improvements in environmental performance have been achieved without expanding the installation surface. This aspect is crucial in plants where space is a limiting factor, allowing maximum energy production without incurring additional costs related to the acquisition and preparation of new installation surfaces.

Table 5.10: General information on the bifacial system for the different PRs

Key parameter		Murcia				
		0.0%	0.5%	1.0%	2.0%	3.0%
Performance ratio (PR)	%	94.3	94.8	95.3	96.3	97.3
Yield	MWh/MWp	2076.3	2087.3	2098.4	2120.4	2142.4
Annual energy production	MWh/year	103,817	104,367	104,918	106,019	107,119
Total amount of energy	MWh	3,114,501	3,131,015	3,147,529	3,180,556	3,213,584
Surface installed	m2	234,741	234,741	234,741	234,741	234,741
Surface used	m2	485,672	485,672	485,672	485,672	485,672
Frontside efficiency	%	21.3				
Bifacial gains (albedo=grass)	%	7.4				

All environmental parameters have shown a decreasing trend as PR increases, implying a lower environmental load. Furthermore, this sensitivity analysis has demonstrated that even small increases in the PR of PV systems could lead to improvements in environmental performance. Furthermore, quantitative results have shown that increases in PR from 94.3% to 97.3% could lead to notable increases in annual energy production, system performance and total energy produced, all without the need to expand the installation surface (Table 5.10).

The sensitivity analysis results highlight the relevance of continuing to develop and implement technological improvements in PV systems. These improvements could not only maximize energy production and system efficiency but also play a crucial role in reducing environmental impact and promoting a transition towards more sustainable energy sources.

5.6 Prospective life cycle assessment for solar photovoltaic technologies

Renewable energy sources are a major route to fighting climate change, and the expansion of solar photovoltaics (solar PVs) is expected to continue apace as unit costs continue to fall [61,62]. From the energy point of view, this emphasizes “clean” and “sustainable” has been achieved from the foreside at some point. On the other hand, the cumulative environmental impacts of considering all aspects of these technologies' rapid expansions have been covered in a relatively limited way, restricting the impact categories and/or performing analysis for full-market existing technologies [63].

LCA, the most preferred cumulative impact assessment tool for analysing technology-to-technology and technology-to-system interactions, comes to the fore in examining the potential impacts of energy technologies. Although there are several implementations on the literature, the conceptualization of traditional LCA remains at the level of analysis of existing technologies and rarely considers future developments. As a result, the dynamic nature of the energy transition and the advancement of emerging technologies cannot be adequately captured by this static LCA analysis. The time-related LCA concept has been asserted to address this conceptualization issue in LCA and integrate it with the energy transition studies.

5.6.1 Typology of time-related life cycle assessment

The range of time-related LCA types has been categorized in the literature: (i) prospective, (ii) retrospective, (iii) ex-ante, (iv) ex-post, (v) lab-scale, (vi) anticipatory, (vii) attributional, (viii) consequential and (ix) dynamic LCA. These definitions are categorized considering three dimensions, in order, which are the real-time, the maturity of technology level, and the causality [64,65].

Prospective LCA or future-oriented LCA attempts to capture potential environmental impacts of both the commercial and emerging technologies in early development at different points in time[66]. Temporal positionality in time scale, it is moving from “present” to “future” while maturity level of technology is low at the “present” point and accelerates to rise as moving in “future” time. In terms of causality dimension, both the causes of a functional unit (attributional LCA) and the effects of functional unit (consequential LCA) can be applied into prospective LCA (hereinafter referred to as pLCA) [65,67]. The schematic illustration of the time-related LCA types is provided in Figure 5.15.

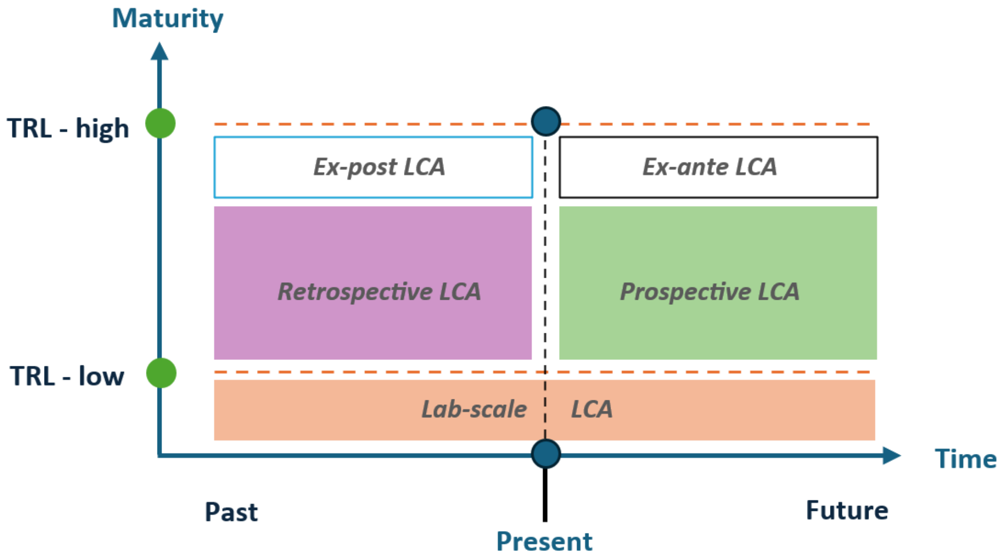


Figure 5.15: The time-related LCA terms, modified from [65]. Abbreviations: TRL, technology readiness level; LCA, life cycle assessment.

Through direct intervention in the foreground and background systems, the real-time LCA concepts can be put into practice. While the LCA user can directly control multiple processes in foreground systems, the LCA user can only indirectly influence pre-existing processes in background systems to a certain extent. Particularly solar PVs, it is crucial to alter the background and foreground systems (primarily life cycle inventories) when performing pLCA analysis. This is due to the further technological advancement of solar cells as the efficiency improvement and material enhancement are significantly accelerated by new processes in parallel with the expansion of the market for solar PV technologies [68]. Nevertheless, “*existing pLCA studies on solar PV technologies only partially reflect these rapid advances, whereas full intervention of foreground and background systems in pLCA analysis remains a significant research gap in the energy and LCA literature”*.

5.6.2 State-of-the art of prospective LCA for solar photovoltaic technologies

In terms of conceptualization and technological level, the application of pLCA analysis in solar technologies is relatively limited. Most often, these studies typically alter the foreground systems while maintaining the life cycle inventories as closely as possible without undergoing significant changes over time. Few of them make minor changes to the background, like altering the electricity mix during background processes.

Nevertheless, the energy transition is dynamic and intricate, with each subsystem's dynamics having the potential to indirectly impact others. For instance, the use of green steel in solar technologies can lower the amount of steel consumed and the amount of energy needed in the future. The life cycle assessment process can yield significant cumulative effects by accounting for even small impacts, such as the consumption of basic materials in the construction of solar PV power plants. This important point has not been thoroughly investigated at the system and technological levels in pLCA studies.

The limited applied pLCA analysis for solar PV technologies focuses mostly on the conceptual design of pLCA for current solar PV technologies [69], on analysing the non-competitive solar PV technologies in the global market [70,71], low-technology readiness level solar PV technologies [72].Despite the fact that the majority of these studies only partially satisfy the fundamental requirements of pLCA, none of them seek to integrate the full pLCA approach: (i) background system - complete change of energy mix, (ii) background system-material life cycle integration, (iii) foreground system- improvement of existing technologies (e.g. efficiency-related changes) and (iv) system technical progress in the foreground (from both in material and energy aspects). As a result, no research using pLCA study (also a pLCA tool) is known to exist [73,74], mostly because of the intricate relationships between the various approaches.

5.6.3 Prospective LCA tools for solar photovoltaic technologies

The incorporation of pLCA into energy system modelling is still in its early stages, so recent studies encourage the growth of this premature stage by presenting diversified approaches. A study presents the modelling framework of an integrated hybrid LCA model covering nine world regions, using prospective industry-related inventories from NEEDS database and energy scenarios from International Energy Agency to generate “THEMIS” framework with a time frame of up to 2050 [75]. This framework later is developed further integrating the life cycle coefficients for a wide range of future power generation technologies [76,77], and then took one more step into progress link to IAM modelling tools [78]. The fact that none of these tools are made with broad applicability in mind, enabling the use of various Integrated Assessment Models (IAMs) or Life Cycle Inventories (LCI) databases, unifies them.

At this point, a more comprehensive tool has been developed following the streamlined approach to integrating IAM prospective scenarios into the LCI database of ecoinvent to allow for pLCA. This tool, ***PRospective EnvironMental Impact asSEment (Premise)***, allows the integration of the expected transformations within five major energy intensive sectors [74](power generation, cement and steel production, freight and passenger road transportation, supply of conventional and alternative fuels); nevertheless, the implementation of pLCA remains largely in the foreground, while changes in the electricity generation mix take centre stage in the background system. The Premise tool operates on the following principles: (i) IAM models’ scenarios are fed into the Premise tool, (ii) the ecoinvent database and wurst are linked to the Premise background, (iii) the Premise tool modifies the available LCIs, (iv) LCA databases based on scenarios for the selected years are generated, (v) the Premise tool offers the option to download and use the database output directly to the Activity Browser, a Python-based Brightway tool’s interface, or it can be fed into the LCA software tools externally [74].

However, these tools meet on a few common shortcomings as follows (i) built for IAM modelling tools, (ii) limited intervene in the background system, (iii) very limited technology variety for energy technologies, particularly solar PV technologies, (iv) not having comprehensive LCIs for power-to-X routes, and finally (v) not involving a material cycle approach. Furthermore, the pLCA tools in use lack comprehensive LCIs for solar PV technologies and modifications to LCIs for energy scenarios aimed towards the future. Particularly, these tools are structured for IAMs, where sectoral divergence is restricted based on users (commercial and residential), rather than technology. The market shares of solar PV technologies do not account for the latest advancements in the industry, such as increased efficiency, technology substitutions, and changes to the materials used. Put simply, there is not a single all-inclusive tool that completely applies the pLCA analysis to energy and solar PV technologies.

For the reasons mentioned above, it is difficult to perform a complete pLCA analysis for solar PV technologies. However, as part of this project, access to the Premise tool - which is limited to a restricted community - is granted by the lead developer of this tool and the Premise tool is connected to the ecoinvent database, wurst and the Activity Browser (Brightway LCA software interface). In the further steps, the developed LCIs of solar PV technologies will be integrated into the GitHub repository and connected to the core main LCI file of the Premise tool. After a few attempts the results could be achieved for IAM model scenarios. However, as has been emphasized several times, the background system alterations of the Premise tool only remain at the electricity mix level.

6 CONCLUSIONS AND RECOMMENDATIONS

This study has presented the LCA results related to innovative photovoltaics systems and their penetration into the grid. More specifically, it shows the results of the environmental assessment of the installation of innovative photovoltaics systems (floating, bifacial and BIPV) in different climate zones (Finland, Germany and Spain) in three-time horizons (2022, 2030 and 2050). In this sense, the environmental impacts of these systems have been evaluated to determine in which stages of the life cycle optimizations could be made to reduce environmental performance. Additionally, a comparative analysis has been carried out with conventional systems (monofacial and BAPV) to determine the environmental performance of the innovative systems compared to the conventional ones. On the other hand, predictions have been made to determine how the environmental impact would affect the penetration of photovoltaics systems in the electrical networks of the three countries, assuming that the proportion increases for 2030 and 2050 compared to 2022. Considering the results obtained, a series of KSIs related to innovative systems and the penetration of renewable energy into power grids have been defined to determine the trend. Finally, a sensitivity analysis has been carried out considering various PR ratios to assess how the innovations developed in the project could impact the environmental performance of one of the innovative systems.

The results obtained have been the following:

- The hotspot analysis has focused on the years 2022, 2030, and 2050, evaluating the environmental impact of innovative PV systems (floating, bifacial, and BIPV), using a cradle-to-grave approach (PV panel manufacturing, transportation, operation, maintenance, and end-of-life). The results have consistently shown that manufacturing has the highest environmental impact, averaging over 96%. Furthermore, a significant reduction in environmental impact over time has been observed due to technological advancements and improved lifecycle management.
- The hotspot analysis of manufacturing components for innovative technologies has shown that PV cells have had the highest impact across all categories. This impact is primarily due to electricity production and usage, along with associated emissions. The mounting system has been the second-largest contributor to environmental impact for floating and bifacial systems, whereas for BIPV, the inverter has been the second component with the highest impact. Over time, a general reduction in environmental impact across all categories has been observed, attributed to technological and efficiency improvements. To reduce these impacts, it is suggested to prioritize perovskite cells, improve inverter efficiency, and optimize module production processes.
- Comparative LCA analysis of three technologies (floating, bifacial, and BIPV) across three climatic zones (Lappeenranta, Munich, and Murcia) has shown that environmental impacts have been highest in Lappeenranta due to its lower solar irradiation. In comparison, impacts have decreased significantly in Munich and Murcia, where solar irradiation is higher. This analysis underscores the importance of considering site-specific factors such as solar irradiation to optimize the environmental performance and energy efficiency of PV technologies.
- Comparative LCA results considering three-time horizons (2022, 2030, and 2050) have shown similar trends across the three technologies, with higher environmental impacts in 2022 and lower impacts in 2050. Utility-scale technologies (floating and bifacial) have shown higher reductions in impacts compared to BIPV. Efficiency improvements, particularly with perovskite cells, have been crucial in reducing the need for materials and infrastructure. BIPV showed higher impacts in 2030 due to its efficiency and lifespan.
- Comparative LCA evaluation of utility-scale PV systems—floating, bifacial, and monofacial—has indicated that bifacial systems generally have had the lowest environmental impact, followed by floating systems, in comparison to monofacial systems. Bifacial systems benefit from their ability to capture solar light from both sides of the panel, increasing energy production and reducing the total environmental footprint. Floating systems also has shown lower impacts due to reduced land use requirements, using bodies of water instead of land. In the comparison of small-scale systems (BIPV

vs BAPV), BIPV has been found to have the most significant environmental impact in all scenarios, partly due to its 90° installation angle, which reduces energy production by capturing less solar radiation. It is recommended to optimize the installation angle to maximize solar gain and promote designs that improve energy efficiency in dense urban environments.

- Based on projected changes in the environmental impact of power grids in Finland, Germany, and Spain for 2022, 2030, and 2050, it has been clear that transitioning to renewable energy sources is crucial for reducing environmental impacts. Significant reductions in non-renewable energy use are expected in these three countries, resulting in a marked decrease in total environmental impact. This implies the need to invest in renewable energy projects, improve energy efficiency, promote technological innovation in renewable energies, and implement policies that encourage their adoption while gradually phasing out subsidies for non-renewable energy sources.
- The evaluation of the KSI has shown that Spain presents the best results in all the selected KSI, attributed to its favourable climatic conditions and high solar irradiation. Bifacial and floating technologies have been found to be the most environmentally sustainable, showing lower environmental footprints, greenhouse gas (GHG) emissions, waste generation, water consumption and land occupation. Furthermore, a significant increase in the proportion of renewable energy in the power grids of the three countries has been projected for 2030 and 2050, reflecting a transition towards more sustainable and efficient energy systems.
- Various sensitivity scenarios based on bifacial technology have been developed in Murcia, increasing PR by 0.5%, 1%, 2% and 3%. The results have indicated that higher PR improved the theoretical efficiency, led to higher annual energy production and system performance without expanding the installation area. This underlines the potential of technological advances to improve energy production and system efficiency while reducing environmental impact, which is crucial for moving towards sustainable energy sources.
- The literature review's conclusion shows that there is a sizable research gap in the literature because the current pLCA studies do not offer thorough analysis that considers changes to the foreground and background systems. In addition, the existing pLCA tools have some common shortcomings: (i) designed for only IAM modelling tools, (ii) very limited intervention in the background system, (iii) restricted technology diversity for energy technologies, especially solar PV technologies, (iv) not including comprehensive LCIs for power-to-X routes and finally (v) not applying a material cycle approach. The latest advances in solar PV technologies are not reflected in the assumptions such as increased efficiency, technology substitution and material change. Of these, partial pLCA implementations are allowed in the pLCA tools. It is found that there is no single comprehensive tool that fully applies pLCA analysis to solar PV technologies.

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Annex I: Bibliography review

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Annex II: Detailed LCA results

Floating PV system

Table S.1: Environmental impact of floating PV technology in Lappeenranta per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	9.55E-05	6.46E-05	6.09E-05
Climate change	kg CO2 eq	1.57E-02	9.82E-03	9.39E-03
Particulate matter	disease inc.	8.94E-10	5.37E-10	5.13E-10
Eutrophication, marine	kg N eq	1.59E-05	1.03E-05	9.34E-06
Eutrophication, freshwater	kg P eq	7.87E-06	6.34E-06	5.11E-06
Eutrophication, terrestrial	mol N eq	1.64E-04	1.09E-04	9.75E-05
Human toxicity, cancer	CTUh	1.82E-11	1.32E-11	1.14E-11
Human toxicity, non-cancer	CTUh	4.94E-10	3.81E-10	3.58E-10
Ionising radiation	kBq U-235 eq	1.54E-03	1.60E-03	1.14E-03
Land use	Pt	6.27E-02	4.62E-02	3.81E-02
Ozone depletion	kg CFC11 eq	5.41E-10	3.96E-10	3.16E-10
Photochemical ozone formation	kg NMVOC eq	5.39E-05	3.57E-05	3.26E-05
Resource use, fossils	MJ	1.95E-01	1.32E-01	1.22E-01
Resource use, minerals and metals	kg Sb eq	4.90E-07	8.65E-07	3.32E-07
Water use	m3 depriv.	1.07E-02	8.36E-03	5.93E-03

Table S.2: Environmental impact of floating PV technology in Munich per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	2.66E-04	1.78E-04	1.68E-04
Climate change	kg CO2 eq	4.47E-02	2.71E-02	2.59E-02
Particulate matter	disease inc.	2.49E-09	1.48E-09	1.41E-09
Eutrophication, marine	kg N eq	4.45E-05	2.85E-05	2.57E-05
Eutrophication, freshwater	kg P eq	2.19E-05	1.75E-05	1.41E-05
Eutrophication, terrestrial	mol N eq	4.56E-04	2.99E-04	2.69E-04
Human toxicity, cancer	CTUh	5.09E-11	3.63E-11	3.13E-11
Human toxicity, non-cancer	CTUh	1.37E-09	1.05E-09	9.87E-10
Ionising radiation	kBq U-235 eq	4.29E-03	4.42E-03	3.14E-03
Land use	Pt	1.75E-01	1.27E-01	1.05E-01
Ozone depletion	kg CFC11 eq	1.52E-09	1.09E-09	8.70E-10
Photochemical ozone formation	kg NMVOC eq	1.50E-04	9.83E-05	8.99E-05
Resource use, fossils	MJ	5.43E-01	3.65E-01	3.37E-01
Resource use, minerals and metals	kg Sb eq	1.36E-06	2.38E-06	9.15E-07
Water use	m3 depriv.	2.99E-02	2.30E-02	1.63E-02

Table S.3: Environmental impact of floating PV technology in Murcia per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	1.80E-04	1.21E-04	1.14E-04
Climate change	kg CO2 eq	3.02E-02	1.83E-02	1.75E-02
Particulate matter	disease inc.	1.68E-09	1.00E-09	9.58E-10
Eutrophication, marine	kg N eq	3.01E-05	1.93E-05	1.74E-05
Eutrophication, freshwater	kg P eq	1.48E-05	1.18E-05	9.53E-06
Eutrophication, terrestrial	mol N eq	3.09E-04	2.02E-04	1.82E-04
Human toxicity, cancer	CTUh	3.45E-11	2.46E-11	2.12E-11
Human toxicity, non-cancer	CTUh	9.30E-10	7.11E-10	6.69E-10
Ionising radiation	kBq U-235 eq	2.90E-03	2.99E-03	2.13E-03
Land use	Pt	1.18E-01	8.61E-02	7.10E-02
Ozone depletion	kg CFC11 eq	1.03E-09	7.39E-10	5.89E-10
Photochemical ozone formation	kg NMVOC eq	1.02E-04	6.66E-05	6.09E-05
Resource use, fossils	MJ	3.67E-01	2.47E-01	2.28E-01
Resource use, minerals and metals	kg Sb eq	9.21E-07	1.61E-06	6.19E-07
Water use	m3 depriv.	2.02E-02	1.56E-02	1.11E-02

Table S.4: Environmental hotspot analysis of floating components manufacturing in Murcia: 2022, 2030 and 205.

Impact category	Unit	Cells	Module	Mounting systems	Electronic installation	Inverter
2022						
Acidification	mol H+ eq	4.42E+01	1.80E+01	1.17E+01	1.82E+01	8.02E+00
Climate change	kg CO2 eq	6.10E+01	1.65E+01	1.83E+01	1.79E+00	2.45E+00
Particulate matter	disease inc.	4.66E+01	2.77E+01	1.74E+01	4.79E+00	3.60E+00
Eutrophication, marine	kg N eq	5.57E+01	1.80E+01	1.69E+01	5.70E+00	3.80E+00
Eutrophication, freshwater	kg P eq	5.20E+01	9.63E+00	1.31E+01	1.73E+01	7.89E+00
Eutrophication, terrestrial	mol N eq	5.34E+01	1.91E+01	1.55E+01	7.56E+00	4.38E+00
Human toxicity, cancer	CTUh	2.66E+01	1.53E+01	3.31E+01	1.48E+01	1.02E+01
Human toxicity, non-cancer	CTUh	1.62E+01	1.38E+01	6.61E+00	4.58E+01	1.75E+01
Ionising radiation	kBq U-235 eq	6.81E+01	5.91E+00	2.08E+01	1.82E+00	3.40E+00
Land use	Pt	4.17E+01	1.63E+01	2.67E+01	9.45E+00	5.78E+00
Ozone depletion	kg CFC11 eq	3.10E+01	5.78E+01	8.89E+00	9.21E-01	1.41E+00
Photochemical ozone formation	kg NMVOC eq	5.17E+01	1.81E+01	1.79E+01	6.66E+00	5.62E+00
Resource use, fossils	MJ	6.19E+01	1.48E+01	1.85E+01	1.69E+00	3.09E+00
Resource use, minerals and metals	kg Sb eq	2.49E+01	1.17E+01	2.25E+00	4.44E+01	1.67E+01
Water use	m3 depriv.	8.66E+01	6.05E+00	3.44E+00	2.37E+00	1.57E+00
2030						
Acidification	mol H+ eq	3.81E+01	1.80E+01	1.17E+01	2.03E+01	1.19E+01

Impact category	Unit	Cells	Module	Mounting systems	Electronic installation	Inverter
Climate change	kg CO2 eq	5.46E+01	1.85E+01	2.05E+01	2.25E+00	4.10E+00
Particulate matter	disease inc.	3.68E+01	3.14E+01	1.97E+01	6.08E+00	6.08E+00
Eutrophication, marine	kg N eq	5.08E+01	1.89E+01	1.77E+01	6.69E+00	5.95E+00
Eutrophication, freshwater	kg P eq	5.48E+01	8.07E+00	1.10E+01	1.62E+01	9.86E+00
Eutrophication, terrestrial	mol N eq	4.92E+01	1.96E+01	1.59E+01	8.65E+00	6.69E+00
Human toxicity, cancer	CTUh	2.49E+01	1.43E+01	3.10E+01	1.55E+01	1.42E+01
Human toxicity, non-cancer	CTUh	1.44E+01	1.21E+01	5.78E+00	4.48E+01	2.29E+01
Ionising radiation	kBq U-235 eq	7.81E+01	3.82E+00	1.35E+01	1.31E+00	3.28E+00
Land use	Pt	4.31E+01	1.50E+01	2.44E+01	9.67E+00	7.88E+00
Ozone depletion	kg CFC11 eq	3.50E+01	5.38E+01	8.27E+00	9.58E-01	1.96E+00
Photochemical ozone formation	kg NMVOC eq	4.69E+01	1.85E+01	1.84E+01	7.64E+00	8.59E+00
Resource use, fossils	MJ	6.04E+01	1.47E+01	1.84E+01	1.88E+00	4.59E+00
Resource use, minerals and metals	kg Sb eq	6.62E+01	4.48E+00	8.59E-01	1.89E+01	9.51E+00
Water use	m3 depriv.	8.75E+01	5.24E+00	2.98E+00	2.30E+00	2.03E+00
2050						
Acidification	mol H+ eq	4.10E+01	1.51E+01	9.78E+00	2.15E+01	1.26E+01
Climate change	kg CO2 eq	6.17E+01	1.51E+01	1.67E+01	2.30E+00	4.20E+00
Particulate matter	disease inc.	4.53E+01	2.59E+01	1.62E+01	6.31E+00	6.32E+00
Eutrophication, marine	kg N eq	5.42E+01	1.65E+01	1.54E+01	7.36E+00	6.55E+00
Eutrophication, freshwater	kg P eq	4.88E+01	7.96E+00	1.08E+01	2.02E+01	1.22E+01
Eutrophication, terrestrial	mol N eq	5.18E+01	1.72E+01	1.40E+01	9.59E+00	7.41E+00
Human toxicity, cancer	CTUh	2.39E+01	1.32E+01	2.85E+01	1.80E+01	1.65E+01
Human toxicity, non-cancer	CTUh	1.31E+01	1.02E+01	4.87E+00	4.75E+01	2.43E+01
Ionising radiation	kBq U-235 eq	7.42E+01	4.28E+00	1.50E+01	1.85E+00	4.62E+00
Land use	Pt	4.09E+01	1.44E+01	2.35E+01	1.17E+01	9.55E+00
Ozone depletion	kg CFC11 eq	3.45E+01	5.36E+01	8.23E+00	1.20E+00	2.46E+00
Photochemical ozone formation	kg NMVOC eq	5.05E+01	1.60E+01	1.58E+01	8.31E+00	9.35E+00
Resource use, fossils	MJ	6.46E+01	1.26E+01	1.58E+01	2.03E+00	4.95E+00
Resource use, minerals and metals	kg Sb eq	1.47E+01	9.28E+00	1.78E+00	4.94E+01	2.48E+01
Water use	m3 depriv.	8.46E+01	5.89E+00	3.34E+00	3.25E+00	2.88E+00

Ground-mounted bifacial PV systems

Table S.5: Environmental impact of ground-mounted bifacial PV technology in Lappeenranta per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	3.27E-04	2.18E-04	2.01E-04
Climate change	kg CO2 eq	4.72E-02	2.84E-02	2.72E-02
Particulate matter	disease inc.	2.87E-09	1.71E-09	1.61E-09
Eutrophication, marine	kg N eq	5.11E-05	3.25E-05	2.92E-05
Eutrophication, freshwater	kg P eq	2.41E-05	1.90E-05	1.52E-05
Eutrophication, terrestrial	mol N eq	5.62E-04	3.67E-04	3.24E-04
Human toxicity, cancer	CTUh	5.73E-11	4.04E-11	3.47E-11
Human toxicity, non-cancer	CTUh	1.60E-09	1.20E-09	1.12E-09
Ionising radiation	kBq U-235 eq	4.25E-03	4.50E-03	3.17E-03
Land use	Pt	3.92E+00	2.63E+00	2.09E+00
Ozone depletion	kg CFC11 eq	8.31E-10	6.30E-10	5.03E-10
Photochemical ozone formation	kg NMVOC eq	1.71E-04	1.12E-04	1.01E-04
Resource use, fossils	MJ	5.66E-01	3.78E-01	3.50E-01
Resource use, minerals and metals	kg Sb eq	1.75E-06	2.75E-06	1.12E-06
Water use	m3 depriv.	3.44E-02	2.62E-02	1.86E-02

Table S.6: Environmental impact of ground-mounted bifacial PV technology in Munich per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	2.57E-04	1.71E-04	1.57E-04
Climate change	kg CO2 eq	3.71E-02	2.22E-02	2.13E-02
Particulate matter	disease inc.	2.26E-09	1.34E-09	1.27E-09
Eutrophication, marine	kg N eq	4.01E-05	2.55E-05	2.29E-05
Eutrophication, freshwater	kg P eq	1.89E-05	1.49E-05	1.19E-05
Eutrophication, terrestrial	mol N eq	4.41E-04	2.87E-04	2.54E-04
Human toxicity, cancer	CTUh	4.51E-11	3.17E-11	2.72E-11
Human toxicity, non-cancer	CTUh	1.26E-09	9.41E-10	8.74E-10
Ionising radiation	kBq U-235 eq	3.34E-03	3.53E-03	2.48E-03
Land use	Pt	3.08E+00	2.06E+00	1.64E+00
Ozone depletion	kg CFC11 eq	6.53E-10	4.94E-10	3.94E-10
Photochemical ozone formation	kg NMVOC eq	1.35E-04	8.74E-05	7.92E-05
Resource use, fossils	MJ	4.45E-01	2.97E-01	2.75E-01
Resource use, minerals and metals	kg Sb eq	1.38E-06	2.15E-06	8.81E-07
Water use	m3 depriv.	2.70E-02	2.05E-02	1.46E-02

Table S.7: Environmental impact of ground-mounted bifacial PV technology in Murcia per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	1.80E-04	1.19E-04	1.10E-04
Climate change	kg CO2 eq	2.60E-02	1.55E-02	1.49E-02
Particulate matter	disease inc.	1.58E-09	9.37E-10	8.83E-10
Eutrophication, marine	kg N eq	2.81E-05	1.78E-05	1.60E-05
Eutrophication, freshwater	kg P eq	1.32E-05	1.04E-05	8.34E-06
Eutrophication, terrestrial	mol N eq	3.09E-04	2.01E-04	1.77E-04
Human toxicity, cancer	CTUh	3.15E-11	2.21E-11	1.90E-11
Human toxicity, non-cancer	CTUh	8.80E-10	6.57E-10	6.10E-10
Ionising radiation	kBq U-235 eq	2.34E-03	2.46E-03	1.73E-03
Land use	Pt	2.16E+00	1.44E+00	1.14E+00
Ozone depletion	kg CFC11 eq	4.57E-10	3.44E-10	2.75E-10
Photochemical ozone formation	kg NMVOC eq	9.42E-05	6.10E-05	5.53E-05
Resource use, fossils	MJ	3.11E-01	2.07E-01	1.92E-01
Resource use, minerals and metals	kg Sb eq	9.62E-07	1.50E-06	6.15E-07
Water use	m3 depriv.	1.89E-02	1.43E-02	1.02E-02

Table S.8: Environmental hotspot analysis of ground-mounted bifacial components manufacturing in Murcia: 2022, 2030 and 2050.

Impact category	Unit	Cells	Module	Mounting systems	Electronic installation	Inverter
2022						
Acidification	mol H+ eq	3.85E+01	1.80E+01	2.12E+01	1.58E+01	6.53E+00
Climate change	kg CO2 eq	5.94E+01	1.30E+01	2.36E+01	1.74E+00	2.23E+00
Particulate matter	disease inc.	4.28E+01	1.84E+01	3.14E+01	4.39E+00	3.09E+00
Eutrophication, marine	kg N eq	5.14E+01	1.74E+01	2.27E+01	5.26E+00	3.28E+00
Eutrophication, freshwater	kg P eq	5.05E+01	9.38E+00	1.62E+01	1.68E+01	7.16E+00
Eutrophication, terrestrial	mol N eq	4.62E+01	1.86E+01	2.51E+01	6.54E+00	3.55E+00
Human toxicity, cancer	CTUh	2.50E+01	6.58E+00	4.56E+01	1.39E+01	8.96E+00
Human toxicity, non-cancer	CTUh	1.53E+01	1.34E+01	1.30E+01	4.30E+01	1.54E+01
Ionising radiation	kBq U-235 eq	7.38E+01	1.23E+01	8.44E+00	1.97E+00	3.45E+00
Land use	Pt	4.76E+01	1.94E+01	1.61E+01	1.08E+01	6.16E+00
Ozone depletion	kg CFC11 eq	6.02E+01	1.84E+01	1.70E+01	1.79E+00	2.57E+00
Photochemical ozone formation	kg NMVOC eq	4.81E+01	1.69E+01	2.39E+01	6.19E+00	4.89E+00
Resource use, fossils	MJ	6.33E+01	1.32E+01	1.89E+01	1.72E+00	2.95E+00
Resource use, minerals and metals	kg Sb eq	2.09E+01	2.39E+01	4.74E+00	3.73E+01	1.31E+01
Water use	m3 depriv.	8.45E+01	5.02E+00	6.71E+00	2.31E+00	1.44E+00
2030						
Acidification	mol H+ eq	3.33E+01	1.80E+01	2.12E+01	1.77E+01	9.74E+00

Impact category	Unit	Cells	Module	Mounting systems	Electronic installation	Inverter
Climate change	kg CO2 eq	5.31E+01	1.45E+01	2.65E+01	2.18E+00	3.72E+00
Particulate matter	disease inc.	3.34E+01	2.06E+01	3.53E+01	5.52E+00	5.17E+00
Eutrophication, marine	kg N eq	4.68E+01	1.82E+01	2.38E+01	6.16E+00	5.11E+00
Eutrophication, freshwater	kg P eq	5.36E+01	7.91E+00	1.36E+01	1.59E+01	8.99E+00
Eutrophication, terrestrial	mol N eq	4.25E+01	1.90E+01	2.56E+01	7.47E+00	5.39E+00
Human toxicity, cancer	CTUh	2.35E+01	6.21E+00	4.30E+01	1.47E+01	1.26E+01
Human toxicity, non-cancer	CTUh	1.37E+01	1.19E+01	1.15E+01	4.26E+01	2.03E+01
Ionising radiation	kBq U-235 eq	8.24E+01	7.72E+00	5.30E+00	1.38E+00	3.23E+00
Land use	Pt	4.86E+01	1.76E+01	1.46E+01	1.09E+01	8.31E+00
Ozone depletion	kg CFC11 eq	6.39E+01	1.61E+01	1.49E+01	1.75E+00	3.35E+00
Photochemical ozone formation	kg NMVOC eq	4.36E+01	1.73E+01	2.45E+01	7.10E+00	7.46E+00
Resource use, fossils	MJ	6.17E+01	1.31E+01	1.89E+01	1.92E+00	4.38E+00
Resource use, minerals and metals	kg Sb eq	6.19E+01	1.01E+01	2.01E+00	1.77E+01	8.29E+00
Water use	m3 depriv.	8.57E+01	4.36E+00	5.84E+00	2.25E+00	1.86E+00
2050						
Acidification	mol H+ eq	3.65E+01	1.55E+01	1.82E+01	1.92E+01	1.05E+01
Climate change	kg CO2 eq	6.03E+01	1.19E+01	2.17E+01	2.25E+00	3.84E+00
Particulate matter	disease inc.	4.18E+01	1.73E+01	2.96E+01	5.83E+00	5.46E+00
Eutrophication, marine	kg N eq	5.03E+01	1.61E+01	2.10E+01	6.85E+00	5.69E+00
Eutrophication, freshwater	kg P eq	4.77E+01	7.83E+00	1.35E+01	1.98E+01	1.12E+01
Eutrophication, terrestrial	mol N eq	4.55E+01	1.70E+01	2.30E+01	8.43E+00	6.09E+00
Human toxicity, cancer	CTUh	2.27E+01	5.75E+00	3.98E+01	1.71E+01	1.47E+01
Human toxicity, non-cancer	CTUh	1.26E+01	1.01E+01	9.79E+00	4.57E+01	2.18E+01
Ionising radiation	kBq U-235 eq	7.87E+01	8.73E+00	5.99E+00	1.97E+00	4.59E+00
Land use	Pt	4.59E+01	1.69E+01	1.40E+01	1.32E+01	1.00E+01
Ozone depletion	kg CFC11 eq	6.28E+01	1.61E+01	1.48E+01	2.19E+00	4.19E+00
Photochemical ozone formation	kg NMVOC eq	4.74E+01	1.52E+01	2.14E+01	7.81E+00	8.21E+00
Resource use, fossils	MJ	6.58E+01	1.12E+01	1.61E+01	2.07E+00	4.71E+00
Resource use, minerals and metals	kg Sb eq	1.29E+01	1.97E+01	3.90E+00	4.32E+01	2.03E+01
Water use	m3 depriv.	8.27E+01	4.91E+00	6.57E+00	3.18E+00	2.63E+00

Ground-mounted monofacial PV systems

Table S.9: Environmental impact of ground-mounted monofacial PV technology in Lappeenranta per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	3.66E-04	2.40E-04	2.32E-04
Climate change	kg CO2 eq	5.41E-02	3.26E-02	3.06E-02
Particulate matter	disease inc.	3.47E-09	2.08E-09	1.84E-09
Eutrophication, marine	kg N eq	5.73E-05	3.64E-05	3.33E-05
Eutrophication, freshwater	kg P eq	2.79E-05	2.16E-05	1.78E-05
Eutrophication, terrestrial	mol N eq	6.22E-04	4.04E-04	3.70E-04
Human toxicity, cancer	CTUh	7.14E-11	4.92E-11	4.08E-11
Human toxicity, non-cancer	CTUh	1.87E-09	1.35E-09	1.32E-09
Ionising radiation	kBq U-235 eq	4.54E-03	4.89E-03	3.62E-03
Land use	Pt	4.39E+00	2.96E+00	2.35E+00
Ozone depletion	kg CFC11 eq	1.84E-09	1.31E-09	6.11E-10
Photochemical ozone formation	kg NMVOC eq	1.94E-04	1.26E-04	1.16E-04
Resource use, fossils	MJ	6.54E-01	4.36E-01	4.01E-01
Resource use, minerals and metals	kg Sb eq	1.77E-06	2.91E-06	1.33E-06
Water use	m3 depriv.	3.74E-02	2.87E-02	2.03E-02

Table S.10: Environmental impact of ground-mounted monofacial PV technology in Munich per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	2.93E-04	1.92E-04	1.86E-04
Climate change	kg CO2 eq	4.34E-02	2.62E-02	2.45E-02
Particulate matter	disease inc.	2.78E-09	1.67E-09	1.48E-09
Eutrophication, marine	kg N eq	4.60E-05	2.92E-05	2.67E-05
Eutrophication, freshwater	kg P eq	2.24E-05	1.73E-05	1.43E-05
Eutrophication, terrestrial	mol N eq	4.99E-04	3.24E-04	2.97E-04
Human toxicity, cancer	CTUh	5.73E-11	3.95E-11	3.27E-11
Human toxicity, non-cancer	CTUh	1.50E-09	1.08E-09	1.06E-09
Ionising radiation	kBq U-235 eq	3.65E-03	3.92E-03	2.90E-03
Land use	Pt	3.52E+00	2.37E+00	1.89E+00
Ozone depletion	kg CFC11 eq	1.48E-09	1.05E-09	4.90E-10
Photochemical ozone formation	kg NMVOC eq	1.56E-04	1.01E-04	9.32E-05
Resource use, fossils	MJ	5.25E-01	3.50E-01	3.21E-01
Resource use, minerals and metals	kg Sb eq	1.42E-06	2.33E-06	1.07E-06
Water use	m3 depriv.	3.00E-02	2.30E-02	1.63E-02

Table S.11: Environmental impact of ground-mounted monofacial PV technology in Murcia per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	2.08E-04	1.37E-04	1.32E-04
Climate change	kg CO2 eq	3.08E-02	1.86E-02	1.74E-02
Particulate matter	disease inc.	1.98E-09	1.18E-09	1.05E-09
Eutrophication, marine	kg N eq	3.26E-05	2.07E-05	1.90E-05
Eutrophication, freshwater	kg P eq	1.59E-05	1.23E-05	1.02E-05
Eutrophication, terrestrial	mol N eq	3.54E-04	2.30E-04	2.11E-04
Human toxicity, cancer	CTUh	4.07E-11	2.80E-11	2.32E-11
Human toxicity, non-cancer	CTUh	1.06E-09	7.66E-10	7.52E-10
Ionising radiation	kBq U-235 eq	2.59E-03	2.79E-03	2.06E-03
Land use	Pt	2.50E+00	1.68E+00	1.34E+00
Ozone depletion	kg CFC11 eq	1.05E-09	7.49E-10	3.48E-10
Photochemical ozone formation	kg NMVOC eq	1.11E-04	7.15E-05	6.61E-05
Resource use, fossils	MJ	3.73E-01	2.48E-01	2.28E-01
Resource use, minerals and metals	kg Sb eq	1.01E-06	1.66E-06	7.58E-07
Water use	m3 depriv.	2.13E-02	1.63E-02	1.15E-02

Building-integrated photovoltaic

Table S.12: Environmental impact of BIPV technology in Lappeenranta per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	4.17E-04	3.49E-04	2.71E-04
Climate change	kg CO2 eq	6.88E-02	5.35E-02	4.29E-02
Particulate matter	disease inc.	3.78E-09	2.85E-09	2.30E-09
Eutrophication, marine	kg N eq	7.44E-05	6.15E-05	4.69E-05
Eutrophication, freshwater	kg P eq	4.06E-05	4.08E-05	2.92E-05
Eutrophication, terrestrial	mol N eq	7.71E-04	6.50E-04	4.92E-04
Human toxicity, cancer	CTUh	5.40E-11	4.80E-11	3.44E-11
Human toxicity, non-cancer	CTUh	1.73E-09	1.59E-09	1.27E-09
Ionising radiation	kBq U-235 eq	6.75E-03	9.06E-03	5.32E-03
Land use	Pt	2.33E-01	2.19E-01	1.53E-01
Ozone depletion	kg CFC11 eq	2.77E-09	2.57E-09	1.76E-09
Photochemical ozone formation	kg NMVOC eq	2.41E-04	2.01E-04	1.56E-04
Resource use, fossils	MJ	8.56E-01	7.42E-01	5.70E-01
Resource use, minerals and metals	kg Sb eq	4.83E-06	7.42E-06	4.09E-06
Water use	m3 depriv.	4.76E-02	4.70E-02	2.61E-02

Table S.13: Environmental impact of BIPV technology in Munich per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	3.72E-04	3.11E-04	2.42E-04
Climate change	kg CO2 eq	6.14E-02	4.78E-02	3.83E-02
Particulate matter	disease inc.	3.37E-09	2.55E-09	2.05E-09
Eutrophication, marine	kg N eq	6.64E-05	5.49E-05	4.19E-05
Eutrophication, freshwater	kg P eq	3.62E-05	3.64E-05	2.61E-05
Eutrophication, terrestrial	mol N eq	6.88E-04	5.81E-04	4.40E-04
Human toxicity, cancer	CTUh	4.81E-11	4.29E-11	3.07E-11
Human toxicity, non-cancer	CTUh	1.54E-09	1.42E-09	1.13E-09
Ionising radiation	kBq U-235 eq	6.02E-03	8.09E-03	4.75E-03
Land use	Pt	2.08E-01	1.96E-01	1.37E-01
Ozone depletion	kg CFC11 eq	2.48E-09	2.30E-09	1.57E-09
Photochemical ozone formation	kg NMVOC eq	2.15E-04	1.80E-04	1.39E-04
Resource use, fossils	MJ	7.64E-01	6.63E-01	5.09E-01
Resource use, minerals and metals	kg Sb eq	4.31E-06	6.63E-06	3.66E-06
Water use	m3 depriv.	4.24E-02	4.20E-02	2.33E-02

Table S.14: Environmental impact of BIPV technology in Murcia per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	2.70E-04	2.26E-04	1.76E-04
Climate change	kg CO2 eq	4.46E-02	3.47E-02	2.79E-02
Particulate matter	disease inc.	2.45E-09	1.85E-09	1.49E-09
Eutrophication, marine	kg N eq	4.82E-05	3.99E-05	3.05E-05
Eutrophication, freshwater	kg P eq	2.63E-05	2.65E-05	1.90E-05
Eutrophication, terrestrial	mol N eq	4.99E-04	4.22E-04	3.20E-04
Human toxicity, cancer	CTUh	3.50E-11	3.11E-11	2.23E-11
Human toxicity, non-cancer	CTUh	1.12E-09	1.03E-09	8.23E-10
Ionising radiation	kBq U-235 eq	4.37E-03	5.88E-03	3.46E-03
Land use	Pt	1.51E-01	1.42E-01	9.94E-02
Ozone depletion	kg CFC11 eq	1.80E-09	1.67E-09	1.14E-09
Photochemical ozone formation	kg NMVOC eq	1.56E-04	1.31E-04	1.01E-04
Resource use, fossils	MJ	5.55E-01	4.81E-01	3.70E-01
Resource use, minerals and metals	kg Sb eq	3.13E-06	4.82E-06	2.66E-06
Water use	m3 depriv.	3.08E-02	3.05E-02	1.69E-02

Table S.15: Environmental hotspot analysis of BIPV components manufacturing in Murcia: 2022, 2030 and 2050.

Impact category	Unit	Cells	Module	Mounting systems	Electronic installation	Inverter
2022						
Acidification	mol H+ eq	4.52E+01	1.25E+01	1.56E+01	4.25E+00	2.24E+01
Climate change	kg CO2 eq	5.97E+01	8.91E+00	1.46E+01	4.54E-01	1.64E+01
Particulate matter	disease inc.	4.85E+01	1.21E+01	2.10E+01	1.19E+00	1.72E+01
Eutrophication, marine	kg N eq	5.25E+01	1.09E+01	1.43E+01	1.27E+00	2.10E+01
Eutrophication, freshwater	kg P eq	4.52E+01	5.45E+00	8.10E+00	3.43E+00	3.78E+01
Eutrophication, terrestrial	mol N eq	5.01E+01	1.18E+01	1.43E+01	1.66E+00	2.21E+01
Human toxicity, cancer	CTUh	4.01E+01	8.32E+00	2.35E+01	5.32E+00	2.27E+01
Human toxicity, non-cancer	CTUh	2.09E+01	1.34E+01	1.12E+01	1.33E+01	4.12E+01
Ionising radiation	kBq U-235 eq	6.97E+01	6.29E+00	4.54E+00	4.32E-01	1.90E+01
Land use	Pt	4.90E+01	1.52E+01	8.85E+00	2.54E+00	2.43E+01
Ozone depletion	kg CFC11 eq	2.72E+01	4.82E+01	3.85E+00	2.67E-01	2.05E+01
Photochemical ozone formation	kg NMVOC eq	5.10E+01	1.09E+01	1.43E+01	1.55E+00	2.24E+01
Resource use, fossils	MJ	6.26E+01	9.22E+00	1.13E+01	4.43E-01	1.65E+01
Resource use, minerals and metals	kg Sb eq	1.13E+01	4.46E+00	5.65E-01	4.59E+00	7.91E+01
Water use	m3 depriv.	8.69E+01	4.46E+00	3.21E+00	5.54E-01	4.91E+00
2030						
Acidification	mol H+ eq	4.01E+01	1.28E+01	1.59E+01	4.95E+00	2.62E+01

Impact category	Unit	Cells	Module	Mounting systems	Electronic installation	Inverter
Climate change	kg CO2 eq	5.28E+01	9.86E+00	1.62E+01	5.71E-01	2.06E+01
Particulate matter	disease inc.	3.85E+01	1.38E+01	2.39E+01	1.54E+00	2.23E+01
Eutrophication, marine	kg N eq	4.75E+01	1.13E+01	1.49E+01	1.50E+00	2.48E+01
Eutrophication, freshwater	kg P eq	4.85E+01	4.63E+00	6.89E+00	3.32E+00	3.66E+01
Eutrophication, terrestrial	mol N eq	4.60E+01	1.20E+01	1.45E+01	1.91E+00	2.55E+01
Human toxicity, cancer	CTUh	3.87E+01	8.00E+00	2.26E+01	5.82E+00	2.49E+01
Human toxicity, non-cancer	CTUh	1.97E+01	1.25E+01	1.04E+01	1.41E+01	4.34E+01
Ionising radiation	kBq U-235 eq	7.90E+01	4.00E+00	2.89E+00	3.13E-01	1.38E+01
Land use	Pt	5.04E+01	1.38E+01	8.04E+00	2.62E+00	2.51E+01
Ozone depletion	kg CFC11 eq	3.04E+01	4.43E+01	3.54E+00	2.79E-01	2.15E+01
Photochemical ozone formation	kg NMVOC eq	4.63E+01	1.11E+01	1.46E+01	1.81E+00	2.61E+01
Resource use, fossils	MJ	6.07E+01	9.10E+00	1.12E+01	4.99E-01	1.85E+01
Resource use, minerals and metals	kg Sb eq	4.41E+01	2.49E+00	3.15E-01	2.91E+00	5.01E+01
Water use	m3 depriv.	8.80E+01	3.85E+00	2.78E+00	5.45E-01	4.83E+00
2050						
Acidification	mol H+ eq	4.02E+01	1.01E+01	1.25E+01	4.89E+00	3.23E+01
Climate change	kg CO2 eq	5.53E+01	7.46E+00	1.22E+01	5.43E-01	2.45E+01
Particulate matter	disease inc.	4.35E+01	1.04E+01	1.81E+01	1.47E+00	2.65E+01
Eutrophication, marine	kg N eq	4.63E+01	9.08E+00	1.19E+01	1.51E+00	3.12E+01
Eutrophication, freshwater	kg P eq	3.74E+01	3.97E+00	5.89E+00	3.57E+00	4.92E+01
Eutrophication, terrestrial	mol N eq	4.43E+01	9.71E+00	1.17E+01	1.94E+00	3.24E+01
Human toxicity, cancer	CTUh	3.44E+01	6.82E+00	1.92E+01	6.24E+00	3.33E+01
Human toxicity, non-cancer	CTUh	1.63E+01	9.59E+00	7.98E+00	1.36E+01	5.25E+01
Ionising radiation	kBq U-235 eq	6.98E+01	4.18E+00	3.02E+00	4.11E-01	2.26E+01
Land use	Pt	4.34E+01	1.21E+01	7.03E+00	2.89E+00	3.46E+01
Ozone depletion	kg CFC11 eq	2.68E+01	3.96E+01	3.16E+00	3.13E-01	3.02E+01
Photochemical ozone formation	kg NMVOC eq	4.55E+01	8.80E+00	1.15E+01	1.79E+00	3.24E+01
Resource use, fossils	MJ	6.02E+01	7.25E+00	8.87E+00	4.99E-01	2.32E+01
Resource use, minerals and metals	kg Sb eq	5.26E+00	2.77E+00	3.50E-01	4.07E+00	8.76E+01
Water use	m3 depriv.	8.35E+01	4.27E+00	3.07E+00	7.58E-01	8.40E+00

Building-applied photovoltaics

Table S.16: Environmental impact of BAPV technology in Lappeenranta per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	3.82E-04	2.69E-04	2.50E-04
Climate change	kg CO2 eq	6.58E-02	4.26E-02	4.13E-02
Particulate matter	disease inc.	3.91E-09	2.49E-09	2.36E-09
Eutrophication, marine	kg N eq	7.01E-05	4.87E-05	4.45E-05
Eutrophication, freshwater	kg P eq	3.68E-05	3.21E-05	2.67E-05
Eutrophication, terrestrial	mol N eq	7.25E-04	5.14E-04	4.66E-04
Human toxicity, cancer	CTUh	5.73E-11	4.21E-11	3.57E-11
Human toxicity, non-cancer	CTUh	1.46E-09	1.20E-09	1.08E-09
Ionising radiation	kBq U-235 eq	6.07E-03	6.67E-03	4.88E-03
Land use	Pt	2.15E-01	1.70E-01	1.42E-01
Ozone depletion	kg CFC11 eq	2.56E-09	1.98E-09	1.64E-09
Photochemical ozone formation	kg NMVOC eq	2.29E-04	1.61E-04	1.49E-04
Resource use, fossils	MJ	8.12E-01	5.80E-01	5.43E-01
Resource use, minerals and metals	kg Sb eq	4.25E-06	5.98E-06	3.69E-06
Water use	m3 depriv.	4.35E-02	3.41E-02	2.42E-02

Table S.17: Environmental impact of BAPV technology in Munich per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	3.10E-04	2.18E-04	2.02E-04
Climate change	kg CO2 eq	5.33E-02	3.45E-02	3.35E-02
Particulate matter	disease inc.	3.17E-09	2.01E-09	1.91E-09
Eutrophication, marine	kg N eq	5.69E-05	3.94E-05	3.60E-05
Eutrophication, freshwater	kg P eq	2.98E-05	2.59E-05	2.16E-05
Eutrophication, terrestrial	mol N eq	5.88E-04	4.16E-04	3.77E-04
Human toxicity, cancer	CTUh	4.64E-11	3.40E-11	2.89E-11
Human toxicity, non-cancer	CTUh	1.18E-09	9.69E-10	8.73E-10
Ionising radiation	kBq U-235 eq	4.92E-03	5.39E-03	3.95E-03
Land use	Pt	1.74E-01	1.37E-01	1.15E-01
Ozone depletion	kg CFC11 eq	2.08E-09	1.60E-09	1.33E-09
Photochemical ozone formation	kg NMVOC eq	1.86E-04	1.31E-04	1.20E-04
Resource use, fossils	MJ	6.59E-01	4.70E-01	4.40E-01
Resource use, minerals and metals	kg Sb eq	3.44E-06	4.84E-06	2.99E-06
Water use	m3 depriv.	3.53E-02	2.76E-02	1.96E-02

Table S.18: Environmental impact of BAPV technology in Murcia per kWh of electricity generated: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	2.18E-04	1.54E-04	1.42E-04
Climate change	kg CO2 eq	3.75E-02	2.43E-02	2.36E-02
Particulate matter	disease inc.	2.23E-09	1.42E-09	1.35E-09
Eutrophication, marine	kg N eq	4.00E-05	2.78E-05	2.54E-05
Eutrophication, freshwater	kg P eq	2.09E-05	1.83E-05	1.52E-05
Eutrophication, terrestrial	mol N eq	4.13E-04	2.93E-04	2.66E-04
Human toxicity, cancer	CTUh	3.26E-11	2.40E-11	2.04E-11
Human toxicity, non-cancer	CTUh	8.32E-10	6.83E-10	6.15E-10
Ionising radiation	kBq U-235 eq	3.46E-03	3.80E-03	2.78E-03
Land use	Pt	1.22E-01	9.67E-02	8.12E-02
Ozone depletion	kg CFC11 eq	1.46E-09	1.13E-09	9.37E-10
Photochemical ozone formation	kg NMVOC eq	1.31E-04	9.21E-05	8.49E-05
Resource use, fossils	MJ	4.63E-01	3.31E-01	3.10E-01
Resource use, minerals and metals	kg Sb eq	2.42E-06	3.41E-06	2.10E-06
Water use	m3 depriv.	2.48E-02	1.94E-02	1.38E-02

Electric grid mix

Table S.19: Environmental impact of Lappeenranta electric grid per kWh of electricity: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	6.44E-04	2.57E-04	3.03E-04
Climate change	kg CO2 eq	1.32E-01	3.00E-02	3.37E-02
Particulate matter	disease inc.	6.29E-09	3.44E-09	3.34E-09
Eutrophication, marine	kg N eq	1.66E-04	5.21E-05	5.25E-05
Eutrophication, freshwater	kg P eq	5.01E-05	1.41E-05	1.69E-05
Eutrophication, terrestrial	mol N eq	2.04E-03	6.26E-04	7.31E-04
Human toxicity, cancer	CTUh	6.53E-11	7.50E-11	8.03E-11
Human toxicity, non-cancer	CTUh	1.62E-09	1.49E-09	1.72E-09
Ionising radiation	kBq U-235 eq	3.45E-01	2.36E-01	5.46E-02
Land use	Pt	5.46E+00	1.17E+00	1.92E+00
Ozone depletion	kg CFC11 eq	3.33E-09	6.49E-10	7.71E-10
Photochemical ozone formation	kg NMVOC eq	5.06E-04	1.54E-04	1.78E-04
Resource use, fossils	MJ	6.12E+00	3.45E+00	1.05E+00
Resource use, minerals and metals	kg Sb eq	3.38E-07	1.35E-06	1.57E-06
Water use	m3 depriv.	6.90E-02	4.00E-02	1.89E-02

Table S.20: Environmental impact of Munich electric grid per kWh of electricity: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	1.09E-03	3.96E-04	1.70E-04
Climate change	kg CO2 eq	4.65E-01	1.27E-01	2.59E-02
Particulate matter	disease inc.	5.72E-09	2.67E-09	1.84E-09
Eutrophication, marine	kg N eq	3.54E-04	9.14E-05	3.01E-05
Eutrophication, freshwater	kg P eq	6.32E-04	5.64E-05	1.46E-05
Eutrophication, terrestrial	mol N eq	2.89E-03	9.47E-04	3.32E-04
Human toxicity, cancer	CTUh	9.40E-11	8.44E-11	5.73E-11
Human toxicity, non-cancer	CTUh	3.02E-09	1.71E-09	9.74E-10
Ionising radiation	kBq U-235 eq	5.43E-02	2.68E-03	2.34E-03
Land use	Pt	3.56E+00	9.67E-01	1.08E+00
Ozone depletion	kg CFC11 eq	4.89E-09	1.55E-09	5.69E-10
Photochemical ozone formation	kg NMVOC eq	7.70E-04	2.88E-04	1.06E-04
Resource use, fossils	MJ	5.92E+00	1.47E+00	3.12E-01
Resource use, minerals and metals	kg Sb eq	6.15E-07	1.28E-06	1.15E-06
Water use	m3 depriv.	2.02E-02	1.13E-02	1.16E-02

Table S.21: Environmental impact of Murcia electric grid per kWh of electricity: 2022, 2030 and 2050.

Impact category	Unit	2022	2030	2050
Acidification	mol H+ eq	8.47E-04	4.69E-04	1.33E-04
Climate change	kg CO2 eq	2.05E-01	1.04E-01	2.08E-02
Particulate matter	disease inc.	4.17E-09	2.16E-09	1.37E-09
Eutrophication, marine	kg N eq	1.59E-04	8.52E-05	2.27E-05
Eutrophication, freshwater	kg P eq	2.88E-05	2.14E-05	1.10E-05
Eutrophication, terrestrial	mol N eq	1.85E-03	9.17E-04	2.44E-04
Human toxicity, cancer	CTUh	6.25E-11	5.38E-11	4.21E-11
Human toxicity, non-cancer	CTUh	1.26E-09	1.06E-09	7.51E-10
Ionising radiation	kBq U-235 eq	1.75E-01	5.35E-02	2.35E-03
Land use	Pt	1.26E+00	1.50E+00	1.70E+00
Ozone depletion	kg CFC11 eq	4.83E-09	2.45E-09	4.61E-10
Photochemical ozone formation	kg NMVOC eq	6.44E-04	3.37E-04	8.16E-05
Resource use, fossils	MJ	5.61E+00	2.25E+00	2.45E-01
Resource use, minerals and metals	kg Sb eq	5.22E-07	1.05E-06	1.42E-06
Water use	m3 depriv.	1.20E-01	8.46E-02	4.91E-02

Performance ratio

Table S.22: Environmental impact of bifacial system in Murcia in 2022 per kWh of electricity changing the PR: 94.3%, 94.8%. 95.3%, 96.3% and 97.3%

Impact category	Unit	94.3%	94.8%	95.3%	96.3%	97.3%
Acidification	mol H+ eq	1.80E-04	1.79E-04	1.78E-04	1.76E-04	1.74E-04
Climate change	kg CO2 eq	2.60E-02	2.58E-02	2.57E-02	2.54E-02	2.51E-02
Particulate matter	disease inc.	1.58E-09	1.57E-09	1.57E-09	1.55E-09	1.53E-09
Eutrophication, marine	kg N eq	2.81E-05	2.79E-05	2.78E-05	2.75E-05	2.72E-05
Eutrophication, freshwater	kg P eq	1.32E-05	1.31E-05	1.31E-05	1.29E-05	1.28E-05
Eutrophication, terrestrial	mol N eq	3.09E-04	3.07E-04	3.06E-04	3.02E-04	2.99E-04
Human toxicity, cancer	CTUh	3.15E-11	3.13E-11	3.12E-11	3.08E-11	3.05E-11
Human toxicity, non-cancer	CTUh	8.80E-10	8.75E-10	8.72E-10	8.61E-10	8.53E-10
Ionising radiation	kBq U-235 eq	2.34E-03	2.32E-03	2.31E-03	2.29E-03	2.26E-03
Land use	Pt	2.16E+00	2.14E+00	2.14E+00	2.11E+00	2.09E+00
Ozone depletion	kg CFC11 eq	4.57E-10	4.54E-10	4.53E-10	4.47E-10	4.43E-10
Photochemical ozone formation	kg NMVOC eq	9.42E-05	9.36E-05	9.33E-05	9.21E-05	9.13E-05
Resource use, fossils	MJ	3.11E-01	3.09E-01	3.08E-01	3.04E-01	3.01E-01
Resource use, minerals and metals	kg Sb eq	9.62E-07	9.56E-07	9.53E-07	9.41E-07	9.32E-07
Water use	m3 depriv.	1.89E-02	1.88E-02	1.87E-02	1.85E-02	1.83E-02