D5.1 - LCA analysis and supply chain optimisation

WP5

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Executive Summary

The present report describes the activities performed within MC2.0 Task 5.1. The main goal of this study is to assess the environmental impact via life cycle assessment (LCA) analysis, to provide an environmental roadmap, and to optimize the supply chain for building integrated (BIPV) technologies developed within this project.

The environmental LCA is performed according to ISO14040[1] and 14044[2] standards, and other available ad-hoc guidelines available for PV or building elements. It includes the life cycle stages from raw material extraction to production of photovoltaic (PV) laminates, until the fabrication of five BIPV end-products, including energy consumption, material production, manufacturing, usage and end-of-life (EOL) treatments. Goal of the assessment is to optimise the BIPV products from a sustainability point of view, providing feedback to the manufacturers on the environmental hotspots identified, but also to demonstrate the resulting low environmental impact and high circularity potential of the BIPV products.

This analysis was made by the European Research Academy (EURAC) thanks to the collaboration with MC2.0 project partners: Toegepast Natuurwetenschappelijk Onderzoek (TNO), innovative Windows (IWIN), Scuola Universitaria Professionale della Svizzera italiana (SUPSI), Glass 2 Power (G2P), Schweizer (SCHW) and Polymer Competence Center Leoben (PCCL), who contributed sharing their inventory data to produce the different products and providing their knowledge and feedback.

The obtained results have been compared with the state of the art, to evaluate the sustainability of the proposed solutions and suggest feedback to improve both the circularity and sustainability of their products. In order to deal with the uncertainty and variability of certain input parameters, a sensitivity analysis was also performed.

The same inventory datasets have been used to develop an environmental roadmap for BIPV products, more specifically, a greenhouse gas (GHG) footprint evolution roadmap over the years in a prospective way, until 2030 and 2050, with a clear definition of the calculation boundaries. This activity was executed via prospective LCA methodology, by modelling the BIPV production in different future expected market scenarios, considering possible future changes of the background production context (in terms of policies and technologies development), for both materials and energy. For that, two different future global market scenarios were considered, a best and a worst-case scenario, in which the policies related to decarbonisation are applied.

Finally, the supply chain of the BIPV products has been optimized, in order to provide a guideline for the front- and back-end manufacturers to improve the material selection process based on the GHG emissions of transport and electricity of each of the main materials required for the BIPV production.

The document is structured as follows: Section 1 will provide an introduction and overview of the LCA framework adopted, and a state-of-the-art analysis of the BIPV environmental sustainability. Section 2 will define the goal and scope of the analysis, while Section 3 will describe the inventory data collected and used.

Section 4 represents the core of the LCA results, while in Section 4 the results are used to model a supply chain optimization. Lastly, Section 6 will summarize the analysis and draft conclusions.

[1] International Organization for Standardization, 2006. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. ISO, Geneva. Available at: https://www.iso.org/standard/37456.html.

[2] International Organization for Standardization, 2006. ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. ISO, Geneva. Available at: https://www.iso.org/standard/38498.html.

Table of Contents

List of Figures

List of tables

Abbreviations and Acronyms

AC	Alternate Current
BIPV	Building Integrated Photovoltaic
BOS	Balance of System
CED	Cumulative Energy Demand
CIGS	Copper Indium Gallium Selenide
c-Si	Crystalline Silicon
EC	European Commission
EED	Energy Efficiency Directive
EF	Environmental Footprint
EOL	End-of-Life
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
ESIA	European Solar Industry Alliance
ETFE	Ethylene Tetrafluoroethylene
EVA	Ethylene Vinyl Acetate
EY	Energy Yield
FU	Functional Unit
GHG	Greenhouse Gas
GMST	Global mean surface temperature
GWP	Global Warming Potential
IEA	International Energy Agency
IGU	Insulated Glass Unit
ITRPV	International Technology Roadmap for Photovoltaic
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSC	Luminescent Solar Concentrator
MMA	Methyl Methacrylate
PCR	Product Category Rule

PERC	Passivated Emitter Rear Cell
PET	Polyethylene Terephthalate
PkBudg500	Peak Budget 500 GtCO2
PMMA	Polymethyl Methacrylate
PO	Polyolefin
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
RES	Renewable Energy Sources
RMIS	Raw Materials Information System
SSP2	Shared Socioeconomic Pathways
TCO	Transparent Conducting Oxide
ZnO	Zinc Oxide

1 Introduction

According to a Joint Research Centre (JRC) study, the exploitation of the European rooftop PV potential only would bring to the production of about 680 TWh/year, representing 24% of the current electricity consumption[3].
According to the International Technology Roadmap for Photovoltaic (ITRPV) 2023 Report[4], the BIPV global installation share is currently negligible, and it is expected to increase only up to 5% of total PV market share by 2033. In Europe the situation is quite different since there are less possibilities for large utility scale power plants in comparison to other countries. Here, the BIPV installations are expected to increase faster than the rest of the world, and the numerous EU funded projects on the topic exemplify this trend.

In Europe, buildings are responsible for about 36% of the GHG emissions and about 97% of the buildings need to be renovated to achieve the EU decarbonization target for the year 2050[5].
It is well known how solar electricity can contribute to GHG emissions reduction: 1 kWh of PV electricity emits about 50 g CO_2-eq, compared to 450 g CO_2-eq of natural gas electricity[6]. For this reason, the European Commission (EC) has established specific directives to boost the energy performances of buildings: the Energy Performance of Buildings Directive EU (EPBD)[7], and the Energy Efficiency Directive (EED)[8], both part of the so called “Clean Energy for all Europeans Package”[9], are among the major drivers for the decarbonization of the building sector.

1.1 Life Cycle Assessment framework

The LCA methodology is used for this report to investigate the environmental performances of BIPV products, since it is currently one of the most used approaches to assess the environmental impacts of products, activities and services.
The method addresses various impact categories – e.g., climate change, use of resources, ecotoxicity, human toxicity – considering all the life cycle stages and including in the analysis not only the main manufacturing processes, but also the extraction and production of the raw materials, the use phase and EOL treatments, such as recycling or final disposal.

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[3] *K. Bodis et al., A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union, August 2019, DOI:10.1016/j.rser.2019.109309*
[4] *VDMA - International Technology Roadmap for Photovoltaic (ITRPV), 2022 Results – April 2023*
[5] *Buildings Performance Institute Europe (BPIE) - A guidebook to European building policy – August 2020*
[6] *NREL - Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update, Sept. 2021*
[7] *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast)*
[8] *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast)*
[9] *European Commission: Directorate-General for Energy, Clean energy for all Europeans, Publications Office, 2019, https://data.europa.eu/doi/10.2833/9937*

This general approach is standardized through the ISO 14000 family of standards, more specifically the ISO 14040:2006[10] and ISO 14044:2006[11], that were created to help the organizations minimize the environmental impact of their operations. The standards describe the LCA principles and framework, dividing the methodology into four phases, as schematized in Figure 1.

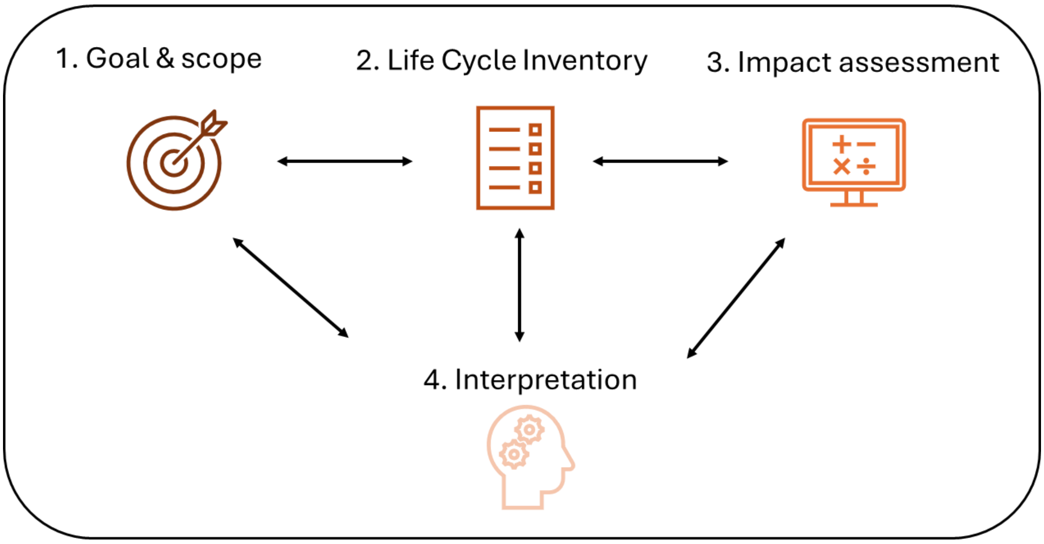

Figure 1 Schematization of the four phases of an LCA study according to ISO 14000 family of standards

The first phase is the definition of the LCA goal and scope, the second one is dedicated to the life cycle inventory (LCI) collection, the third one refers to the life cycle impact assessment (LCIA) phase, and the last one represents the interpretation of the obtained results. The general framework is standardized to guarantee transparency and reproducibility, but the methodological details are not regulated and depend on the type of product or service analysed. Depending on the country location of the study, the scope and the type of product, service or organization, there might be some specific guidelines to follow. For example, to obtain an Environmental Product Declaration (EPD), the LCA study must follow the Product Category Rule (PCR) for the specific product under analysis. For the PV sector, there are several guidelines available: the IEA PVPS Task 12 Guideline 2020[12], and several PCRs such as the one available at EPD Norway[13].

Since there are no ad-hoc PCRs available for BIPV product, current available EPDs for this product category take as a reference both PCRs for construction products and PV systems: as example following

[10] International Organization for Standardization, 2006. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. ISO, Geneva. Available at: https://www.iso.org/standard/37456.html.

[11] International Organization for Standardization, 2006. ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. ISO, Geneva. Available at: https://www.iso.org/standard/38498.html.

[12] Frischknecht, R., Stolz, P., Heath, G., Raugei, M., Sinha, P., de Wild-Scholten, M., 2020. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 4th edition. IEA PVPS Task 12, International Energy Agency Photovoltaic Power Systems Programme. Available at: https://iea-pvps.org/wp-content/uploads/2020/07/IEA_Task12_LCA_Guidelines.pdf.

[13] EPD Norway, 2022. NPCR 029:2022 Part B for Photovoltaic Modules. EPD Norway, Oslo. Available at: https://www.epd-norge.no/getfile.php/1323443-1650542497/PCRer/NPCR%20029%202022%20Part%20B%20for%20photovoltaic%20modules%203103%202022.pdf.

the PCR for construction products[14] and complementary standards (e.g., NPCR 022:2022 v2.0[15] for roof waterproofing and NPCR 010:2019 v3.0[16] for building boards for BIPV products).
The guidelines also suggest the environmental impact categories to measure. In Europe, it is common practice to refer to the Environmental Footprint (EF) 3.1[17] impact method, which includes 16 impact categories, such as climate change, the eutrophication, the land use, the resource depletion, the acidification, the ozone depletion, the eco- and human toxicity. The methodology also suggests normalization and weighting factors, to sum all the impact categories in one single score and ease the visualization of the results (Figure 2).

[14] EPD International, 2024. PCR 2019:14, v1.3.4, Specific for Construction Product. EPD International, Stockholm. Available at: https://api.environdec.com/api/v1/EPDLibrary/Files/fe17e14b-3ff4-4ab3-07a6-08dc685f3598/Data.
[15] EPD Norway, 2022. NPCR 022:2022 Part B for Roof Waterproofing. EPD Norway, Oslo. Available at: https://www.epd-norge.no/getfile.php/1323428-1727955961/PCRer/NPCR%20022%202022%20Part_B_for_Roof_waterproofing%203103%202022.pdf.
[16] EPD Norway, 2019. NPCR 010:2019 Part B for Building Boards. EPD Norway, Oslo. Available at: https://www.epd-norge.no/getfile.php/1310365-1556546489/PCRer/NPCR%20010%202019%20Part%20B%20for%20Building%20Boards%20final%20version%20.pdf.
[17] Andreasi Bassi S., Biganzoli F., Ferrara N., Amadei A., Valente A., Sala S., Ardente F., Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/798894, JRC130796.

Figure 2 Representation of the different impact categories of the EF 3.1 impact method18

[18] Andreasi Bassi S., Biganzoli F., Ferrara N., Amadei A., Valente A., Sala S., Ardente F., Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/798894, JRC130796.

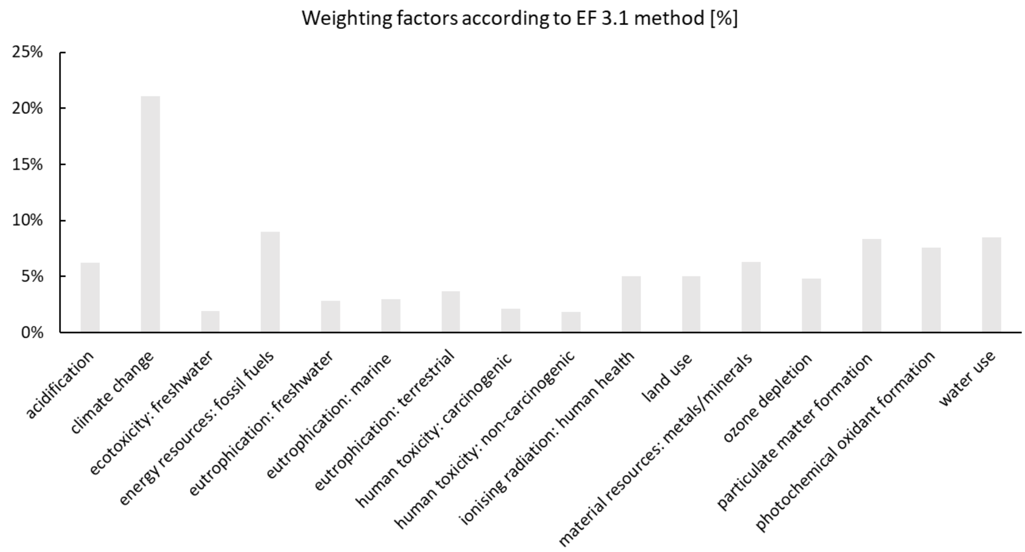

Figure 3 Weighting factors according to the EF 3.1 impact assessment method

Depending on the focus of the study, an LCA can be either attributional if the focus is the evaluation of the impact of a specific product, consequential if the aim is to analyze the effect of the variation of specific parameters, or comparative if the goal is to compare two or more products. Another more recent LCA technique is the prospective one, often also referred to as ex-ante LCA, in which the LCA is applied considering some future scenarios for the production of the products and raw materials. All these techniques are combined in this study to highlight different aspects of the BIPV products analysed.

1.2 State-of-the-art

While literature is dense with studies on environmental LCA of PV systems, there is still a gap regarding the application and harmonization of the LCA methodology to the BIPV sector, since this is a class of product with a very little share on the market. From a Scopus search performed in October 2024, only 46 documents related to the keywords “LCA and BIPV” are found, versus 724 related to the keywords “LCA and PV”. Thus, the aim of this study is to contribute and reduce the literature gap on the topic and help to harmonize the methodology for integrated PV applications. As in

Table 1, the majority of the LCA studies available in literature are focused on climate change or energy demand, while the focus of this report is on all the environmental footprint indicators, with a major attention on the climate change one.

In order to provide a benchmark comparison with similar products, the results of this study have been compared with those available in public EPDs. Figure 4 and Figure 5 show the benchmark for insulated glass unit (IGU) window products and other building envelope elements, respectively. For window products, the emissions of BIPV IGU windows are on average slightly higher than the traditional IGU windows, as expected due to the addition of the PV laminate. The LSC-based BIPV product was compared with a literature available study[19], with relatively lower emissions than the ones obtained in this study. The detailed analysis of the GHG emissions is explained in further detail in Section 4.

[19]Muteri, V., Longo, S., Traverso, M., Palumbo, E., Bua, L., Cellura, M., Testa, D., & Guarino, F. (2023). Life cycle assessment of luminescent solar concentrators integrated into a smart window. Energies, 16(4), 1869. https://doi.org/10.3390/en16041869

Table 1 Literature review of the most recent paper on the LCA applied to BIPV topic

Source	Brief description	Impact category analysed
A. Virtuani et al. 2023[20]	Study of the Climate change emissions of electricity generated from vertical and optimal oriented PV applied on buildings, in different locations and orientations	Climate change
S. Aguacil et al., 2024[21]	LCC, LCC and multi-criteria analysis applied on BIPV, applied to a 1970's residential building case study, examining different refurbishment scenarios	Climate Change, Cost, CED
F. Rossi et al., 2024[22]	Consequential and prospective life cycle assessment and economic analysis of perovskite based roof and façade BIPV, using 1 square meter or 1 kWh as functional unit	Selected Environmental Footprint Indicators (Including Climate Change), Cost, Energy demand
F. M. Amoruso et al., 2023[23]	LCA and LCC of BIPV systems in timber-hybrid building extensions and envelope renovation systems of three exemplary buildings in the Republic of Korea: apartment, mixed-use commercial/industrial, and low-rise multi-unit residential	Climate Change, Cost, Energy demand
W. Fan et al., 2023[24]	Life cycle evaluation theory to assess the carbon emissions of photovoltaic curtain walls, applied with the functional unit of 1 kWp	Climate change
J. McCarty et al., 2023[25]	Study based on a typical Swiss residential building with adjacent vegetation, including various BIPV facade permutations with different cell types, module orientations, inverter types, facade azimuths, grid emissions profiles, and tree planting scenarios	Climate change
H. Amini Toosi et al., 2022[26]	Assessing the potential of building-integrated photovoltaics and thermal energy storage systems, applied to a residential multi-family building in Italy as case study	Climate change
V. Muteri et al., 2023[27]	Energy and environmental aspects of an innovative Photovoltaic Luminescent Solar Concentrator Window	Selected Environmental Footprint Indicators (including Climate Change)

[20] Virtuani, A., et al., 2023. The carbon intensity of integrated photovoltaics. Cell Reports Physical Science, 4(10), 101200. Available at: https://www.sciencedirect.com/science/article/pii/S2542435123004002.

[21] S. Aguacil, S. Duque, S. Lufkin, E. Rey. (2024). Designing with building-integrated photovoltaics (BIPV): A pathway to decarbonize residential buildings, Journal of Building Engineering, Volume 96,2024, 110486, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2024.110486.

[22] Federico Rossi et al., 2024. Unveiling the potential of perovskite solar systems in building integrated installations: A consequential and prospective life cycle assessment and economic analysis, Energy and Buildings, Volume 312, 2024, 114214, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2024.114214.

[23] Amoruso, F. M., & Schuetze, T. (2023). Carbon Life Cycle Assessment and Costing of Building Integrated Photovoltaic Systems for Deep Low-Carbon Renovation. *Sustainability*, *15*(12), 9460. https://doi.org/10.3390/su15129460

[24] Fan, W., Zhang, J., Zhou, J., Li, C., Hu, J., Hu, F., & Nie, Z. (2023). LCA and Scenario Analysis of Building Carbon Emission Reduction: The Influencing Factors of the Carbon Emission of a Photovoltaic Curtain Wall. Energies, 16(11), 4501. https://doi.org/10.3390/en16114501

[25] McCarty, J., Waibel, C., Galimshina, A., Hollberg, A., & Schlueter, A. (2023). Do we need a saw? Carbon-based analysis of facade BIPV performance under partial shading from nearby trees. Journal of Physics: Conference Series, 2600(4), 042002. https://doi.org/10.1088/1742-6596/2600/4/042002

[26] Amini Toosi, H., Lavagna, M., Leonforte, F., Del Pero, C., & Aste, N. (2022). Building decarbonization: Assessing the potential of building-integrated photovoltaics and thermal energy storage systems. *Energy Reports*, 8, 574-581. https://doi.org/10.1016/j.egyr.2022.11.257

[27] Muteri, V., Longo, S., Traverso, M., Palumbo, E., Bua, L., Cellura, M., Testa, D., & Guarino, F. (2023). Life cycle assessment of luminescent solar concentrators integrated into a smart window. Energies, 16(4), 1869. https://doi.org/10.3390/en16041869

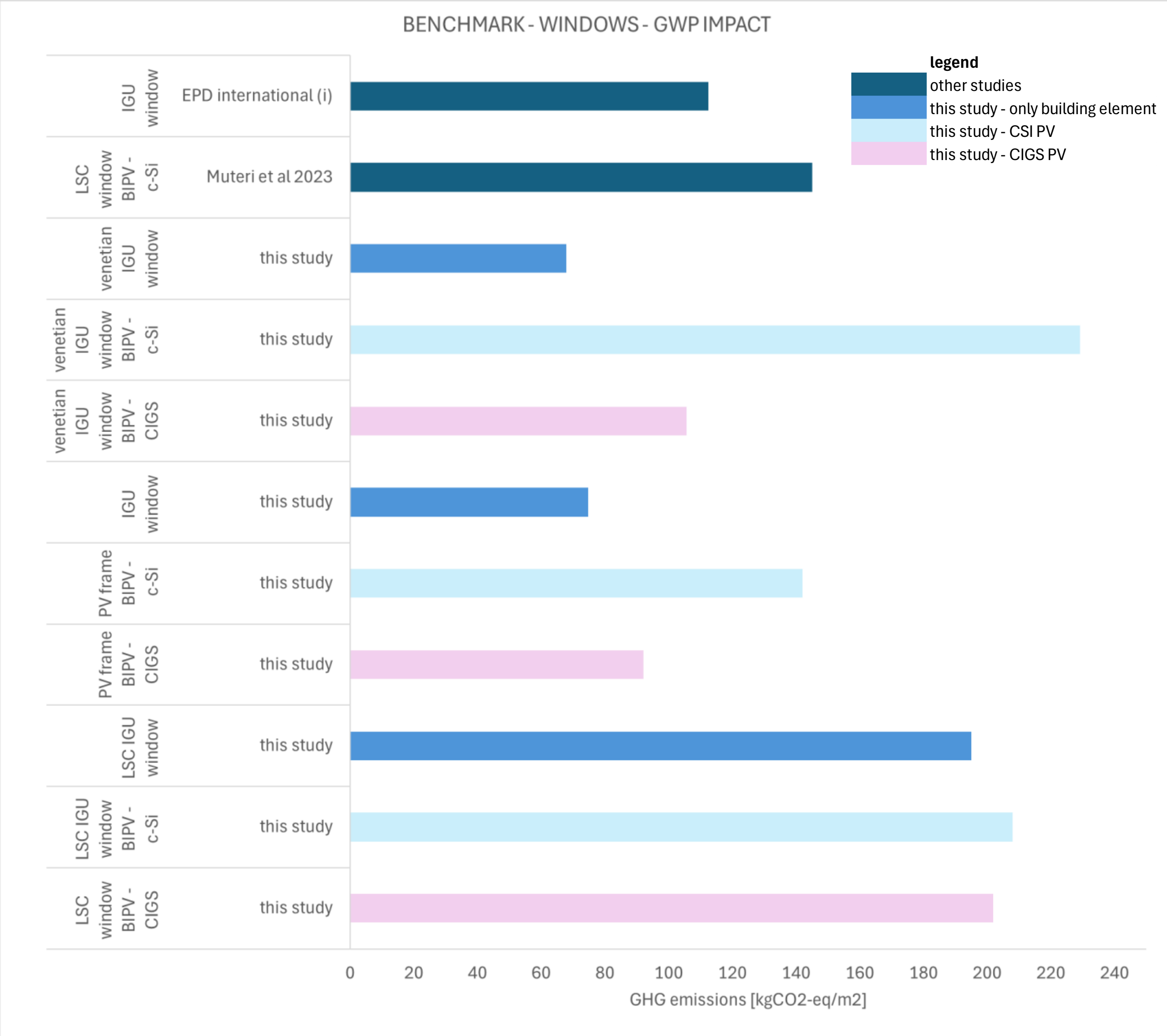

Figure 4 Benchmark analysis for window BIPV: comparison between the GHG cradle-to-gate emissions results obtained from this study for IGU window products, with results for IGU windows from available EPDs or literature studies. Sources: (i)[28]

The benchmark analysis for façade and roof BIPV is presented instead in Figure 5. In this case, the obtained results for the GHG emission of the MC2.0 BIPV products were compared with the results from various EPDs of other similar BIPV products, or with EPDs of traditional clay or steel roof tiles and façades. It is possible to

[28] Average from various sources:
https://environdec.com/library/epd7443;
https://data.environdec.com/datasetdetail/process.xhtml?uuid=27d29e96-6544-44d6-90e4-755384184bf6&version=05.00.002&stock=Environdata;
https://api.environdec.com/api/v1/EPDLibrary/Files/b2f94eb5-3deb-4ce3-79f8-08da491c4cdf/Data

observe how the impact of the steel roof tile BIPV from this study is on overall lower than the benchmarks, while the impact of the façade BIPV from this study is lower in the CIGS configuration, higher in the c-Si one.

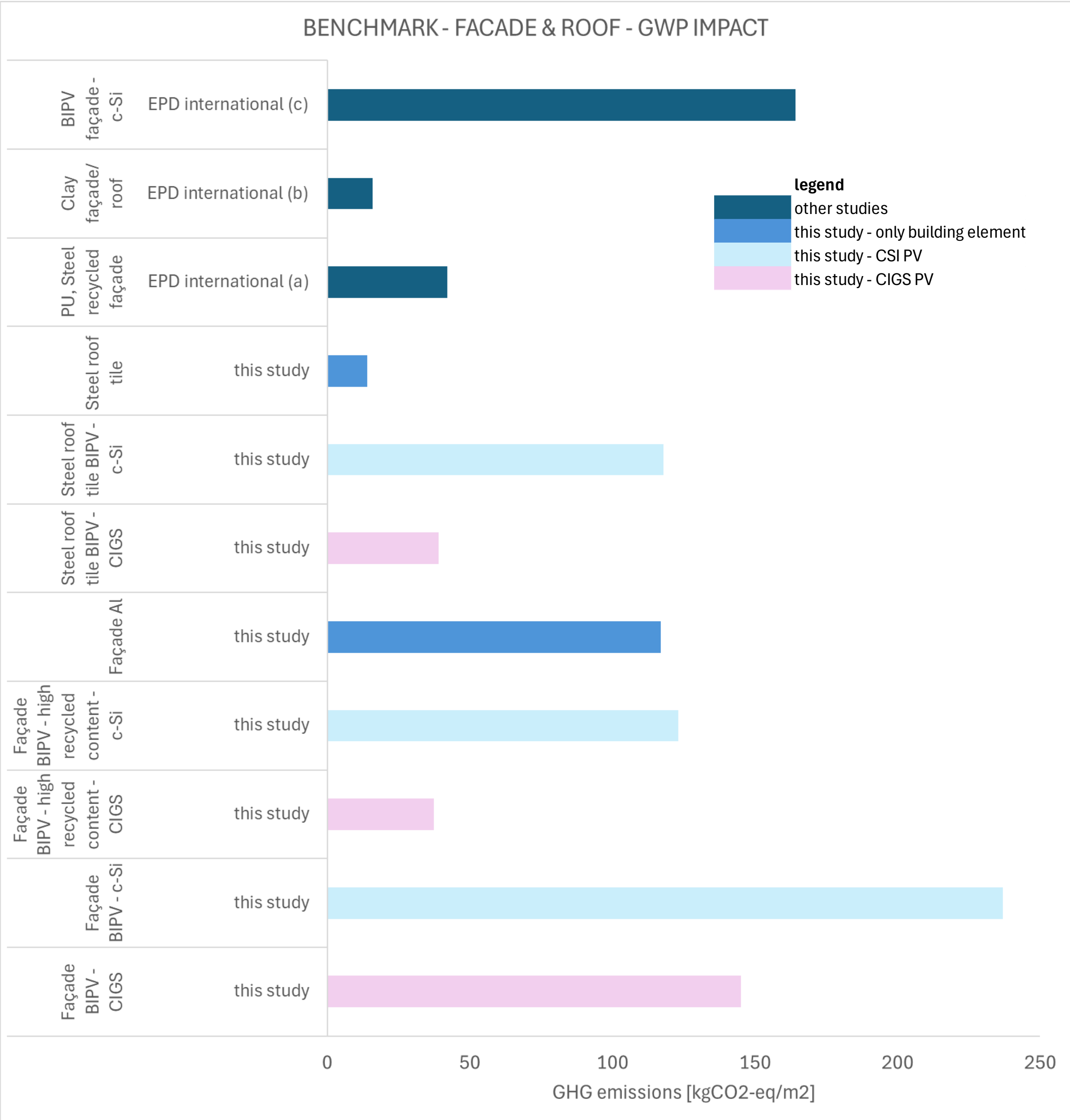

Figure 5 Benchmark analysis for façades and roof tile BIPV products: comparison between the GHG cradle-to-gate emissions results obtained from this study for the façade and roof products, with results from available EPDs, for other BIPV typed and building elements without PV. Sources: (a)[29], (b)[30], (c)[31]

[29] https://www.environdec.com/library/epd9891
[30] https://ecosmdp.eco-platform.org/datasetdetail/process.xhtml?uuid=edf59060-b751-486b-96ef-af142b3317d9&version=00.01.003&lang=en
[31] Average from various sources:
https://www.epddanmark.dk/media/x52h55lx/md-23108-en.pdf;

The following document is structured in a way that follows the steps of the LCA methodology: the second chapter is dedicated to the first goal and scope phase of the LCA, in which the settings of the analysis, the methodology used, and the system boundaries are explained. The third chapter is dedicated to the selection of inventory sources used for the LCA, while the fourth chapter is dedicated to the results evaluation and the fifth chapter uses the obtained results to ideally optimize the supply chain from the GHG emissions point of view. The final chapter is meant to summarize and interpret the obtained results, to be used as a guideline for other LCA practitioners or for BIPV eco-designers.

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https://itb.lca-data.com/datasetdetail/process.xhtml?uuid=fcae9cab-5726-4136-ae44-0ba796b79d23&version=00.03.000&lang=en;
https://ecosmdp.eco-platform.org/datasetdetail/process.xhtml?uuid=eeb0ba93-eda3-48e1-aac6-9d499a5c552a&version=00.01.001&lang=en;
https://ecosmdp.eco-platform.org/datasetdetail/process.xhtml?uuid=3a09cf96-a829-4090-96af-550f9b9bff55&version=00.01.000&lang=en

2 Goal & scope

2.1 Goal

The first step of a life cycle assessment is the definition of the goal and the scope of the analysis, in which the system boundary is set. Scope of the report is not to compare the products within themselves, but rather to prove that the BIPV products are competitive in terms of environmental impact, and to find possible environmental hotspots that will need to be further addressed by the BIPV producers.

To evaluate the competitiveness of the BIPV products, the obtained results have been compared with the impact of the mainstream crystalline silicon (c-Si) mounted PV technology, and with traditional building elements.

The products here evaluated are illustrated in

Figure 6. Two types of PV laminates developed in the first front-end line of the MC2.0 manufacturing stage are included: one laminate is made with c-Si cells and the other with copper indium gallium selenide (CIGS) thin film technology. These two types of PV laminates are assumed to be integrated into five BIPV products, in the second back-end line step of the mass customization manufacturing stage:

- Roof tile BIPV
- Façade BIPV
- Venetian window with PV blinds
- LSC transparent window BIPV
- Window with PV frame

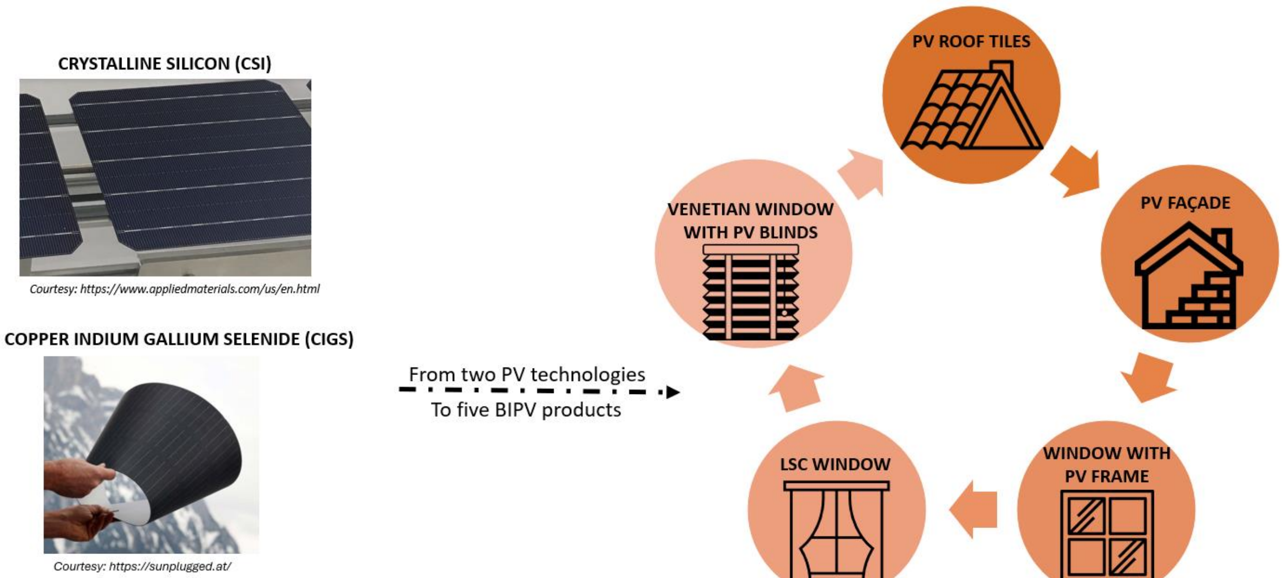


Figure 6 Schematic representation of the five BIPV products analysed in this report

Different system boundaries and functional units of have been analysed in the LCA, at different life cycle stages as shown in Figure 7: raw materials extraction, PV laminate production, integration in BIPV, usage, and recycling as, including the transport in each stage.

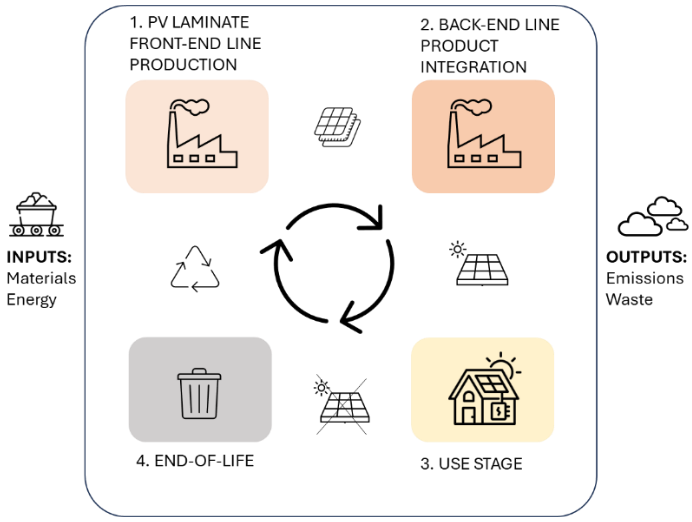


Figure 7 Life cycle schematization for the MC2.0 analysis

Since the BIPV products do not have a relevant market share yet, but they are expected to expand in the next years, a prospective LCA was performed in a second step, to evaluate the effect on the environmental impacts of the current and future climate-related policies, up to 2050.

The OpenLCA[32] software and the Activity Browser[33] tool has been used to perform the traditional and prospective LCA, respectively. With respect to OpenLCA, the Activity Browser allows to update the background processes according to future scenarios, as explained in Section 4.1.5.

The study is mainly addressed to the manufacturers of the various BIPV products of the MC2.0 itself, to provide them feedback on the environmental impact of their products and identify hotspots along the value chain, to improve eco-design and circularity. But it is also targeted to manufacturers of similar products, and to researchers in the LCA field for building and photovoltaic sector, to compare their analysis.

2.2 Scope

The methodology used for this study is based on the ISO 14040/44 standards, and on guidelines that are more specific of the PV sectors, as the ones provided by the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) Task 12 for the PV sector[12]. Since these guidelines are more specific for the PV modules, while the BIPV products fit both in the construction and electric equipment categories, the LCA has been tailored to the BIPV with specific assumptions.

The LCIA (third phase of the LCA analysis according to ISO 14040 standard) is divided into five cases, as described in Table 2. Each case focuses on a different aspect of the BIPV products' sustainability. The first, second and third are dedicated respectively to the PV laminate, the BIPV product, and the entire system with balance of system (BOS). The fourth case is focused on the EOL, more in detail on the effect of recycling selected materials. Since the BIPV products are new products, specific recycling processes for BIPV are not available yet, so only the recycling of selected materials from the building integration part is considered. A deeper analysis of the circularity and recycling of the five products is under development within Task 5.2 and 5.3 of this project. Finally, the fifth case is focused on the prospective LCA, to estimate how the GHG

[32] GreenDelta GmbH. (2023). openLCA (Version 2.0) [Software]. GreenDelta GmbH. Available at: https://www.openlca.org/download/

[33] Steubing, B., Visscher, M., & van der Meide, M. (2024). Activity Browser (Version 2.10.3) [Software]. Leiden University. Available at: https://github.com/LCA-ActivityBrowser/activity-browser

emissions from BIPV production could change in 2030 or 2050, thanks to the effect of foreseen changes in the upstream processes according to future climate-related policies. More details on the scenarios assumed are available in Section 3. These projections are not representing exact forecasts, but can be useful to provide an estimate of the possible pathways for BIPV products in the future, when they might have a relevant share in the market.

Table 2 Description of the cases of the LCA analysis used in this report.

	FOCUS OF LCA ANALYSIS	***PV TECHNOLOGY/PRODUCT***	***FUNCTIONAL UNIT***
CASE 1 LAMINATE	PV laminate	*Technologies*: c-Si, CIGS *Frontsheet*: glass, polymers	m^2 of laminate
CASE 2 BIPV PRODUCT	PV laminate + building element	*Technologies*: c-Si, CIGS *Frontsheet*: glass, polymer *BIPV applications*: roof tiles, façade, Venetian window with PV blinds, LSC transparent window, window with PV frame	m^2 of BIPV product
CASE 3 BIPV INTEGRATION	PV laminate + building element + BOS	*Technologies*: c-Si, CIGS *Frontsheet*: glass, polymer *BIPV applications*: roof tiles, façade, Venetian window with PV blinds, LSC transparent window, window with PV frame	kWp of BIPV product; kWh of electricity produced
CASE 4 EOL	PV laminate + building element	*Technologies*: c-Si, CIGS *Frontsheet*: glass, polymer BIPV applications: roof tiles, façade, Venetian window with PV blinds, LSC transparent window, window with PV frame *Recycled materials*: glass, aluminium, steel	m^2 of BIPV product
CASE 5 PROSPECTIVE LCA	PV laminate + building element	*Technologies*: c-Si, CIGS *Frontsheet*: glass, polymers *BIPV applications*: roof tiles, façade, Venetian window with PV blinds, LSC transparent window, window with PV frame *Prospective scenarios*: best case and worst case by 2030 and 2050	m^2 of BIPV product

The impact categories to be analysed were selected in accordance with the LCA guidelines IEA PVPS 2020[12]. For this reason, the EF 3.1[17] indicators were selected. A more detailed explanation of the indicators is available in Section 1.1. The results obtained for all these categories were also normalized and weighted, using normalization and weighting factors according to the EF 3.1 methodology itself, in order to obtain a single score dimensionless result. This step allows to understand which impact categories are the most important for this type of product.

To expand the analysis from module level to system level, the BOS was added and the impact evaluated for 1 m² of BIPV was converted to 1 kWp of BIPV installed capacity, by using the BIPV module efficiency, expressed in kWp per square meter BIPV module. The efficiency of the different products was estimated based on the efficiency of the PV laminates, the PV area coverage, and feedback from the producers, and is reported in Table 3. Since a real estimation on the efficiency was not available by the end of this task, a sensitivity analysis with different efficiency values for the different products has been performed.

The PV laminates present a higher efficiency, since this is calculated before the integration in a BIPV system.

The products have different efficiencies, depending on their PV area coverage. Window BIPVs are expected to have a lower efficiency, except for the venetian BIPV since the venetians are considered to be in the closed position. On the other hand, fully transparent products – LSC transparent window and window with PV frame – have the advantage of being more building-integrable. In the LSC transparent window the efficiency reduction is the highest, since in this product the PV cells do not receive direct light, but the light is scattered thanks to nanoparticles inserted in the window, increasing the losses.

Table 3 Estimation of the BIPV efficiency per BIPV and PV cell type. *Values of the efficiency are estimated based on the producers' feedback, since official final values will be only available towards the end of the project. For this reason, a sensitivity analysis has been performed.

BIPV PRODUCT	PV TECHNOLOGY	BIPV ESTIMATED EFFICIENCY* [kWp per square meter]
PV laminate	CIGS	0.18
	c-Si	0.20
Roof tile	CIGS	0.140
	c-Si	0.154
Façade	CIGS	0.153
	c-Si	0.167
LSC transparent window	CIGS	0.009
	c-Si	0.010
Window with PV frame	CIGS	0.037
	c-Si	0.040
Venetian window	CIGS	0.144
	c-Si	0.152

To pass from system level to electricity generated level, adding the use stage of the BIPV installed, a lifetime of 30 years has been assumed for the five products, in line with the cited guidelines.

The system level environmental impact has been converted form the functional unit of 1 kWp installed capacity to 1 kWh of alternate current (AC) electricity generated, by using the total energy yield (EY) estimated for each product among the lifetime.

For this step, the method to estimate the EY is based on the study of Virtuani et al., 2023[20], where the EY was calculated considering the different PV orientations, tilts and installation locations, as in Figure 8, Table 4 and

Table 5.

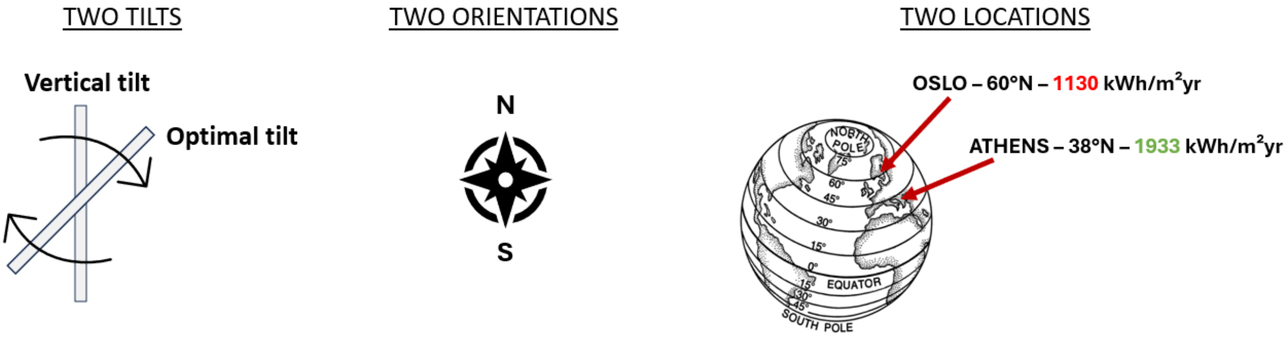


Figure 8 Schematic representation of the tilts, orientations and installation locations considered in the analysis.

An optimal tilt has been considered for the roof tile BIPV, and for the comparison with a traditional standard roof mounted PV, while a vertical tilt has been considered for the façade and window BIPV products.

Since the optimization of the orientation is not always possible in BIPV installations, a best south and a worst north orientation have been considered. Two locations with high and low irradiation have been assumed (Oslo and Athens) and taken as reference for the GHG emissions of the grid electricity mix, to compare the BIPV products with a traditional building that uses electricity from the grid.

Table 4 Energy yield for 30 years, for optimal and vertical tilts, south and north orientation, and in two installation locations. Source: Virtuani et al., 2023[20]

	ENERGY YIELD in 30 years [MWh/kWp]			
	OPTIMAL TILT		VERTICAL TILT	
Orientation	*Athens*	*Oslo*	*Athens*	*Oslo*
South	44	25	25	19
North	9	5	5	4

Table 5 Carbon intensity of the grid and renewable share in the grid, for the selected installation locations.

	YEAR	LITERATURE SOURCE	UNIT	ATHENS	OSLO
Electricity mix carbon intensity	2022	Virtuani et al., 2023[20]	g CO_2-eq/kWh	780	31
RES share	2022	IRENA Energy Profiles[34]	%	43	98

[34]International Renewable Energy Agency (IRENA). (2024). Energy Profiles. IRENA. Available at: https://www.irena.org/Data/Energy-Profiles

3 Life Cycle Inventory

The second stage of the LCA analysis according to the ISO 14040 standard is the LCI data collection. For this study, both primary and secondary data have been used. Primary inventory data were directly collected by MC2.0 project partners, and secondary data were selected among the ones available from comprehensive Ecoinvent 3.9[35] database, scientific literature or public LCA inventories. All primary data are confidential and cannot be shared within this report.

The primary data have been used for the main production processes, so called "foreground inventory", while secondary data have been used for the upstream and downstream processes, so called "background inventory", or to fill primary data gaps. A schematic representation of the BIPV life cycle stages is available in

Figure 9, with the classification into foreground and background processes.

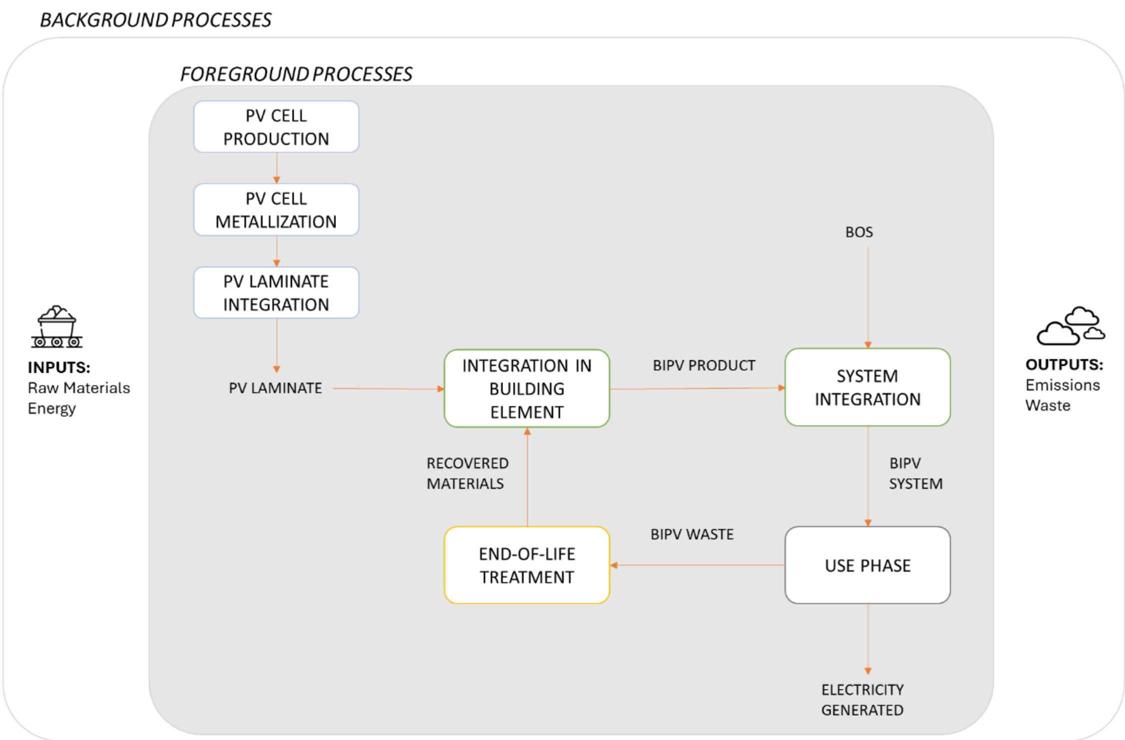


Figure 9 Schematization of the BIPV production process, with definition of background and foreground processes

specific data collection tables have been prepared and shared with MC2.0 partners to collect primary data, as shown in Figure 10. The partners have filled the inventory with their production data, and the inventories have been refined within the course of the project in an iterative process.

[35]Ecoinvent Centre. (2024). ecoinvent database version 3.9. ecoinvent. Available at: https://ecoinvent.org/database/

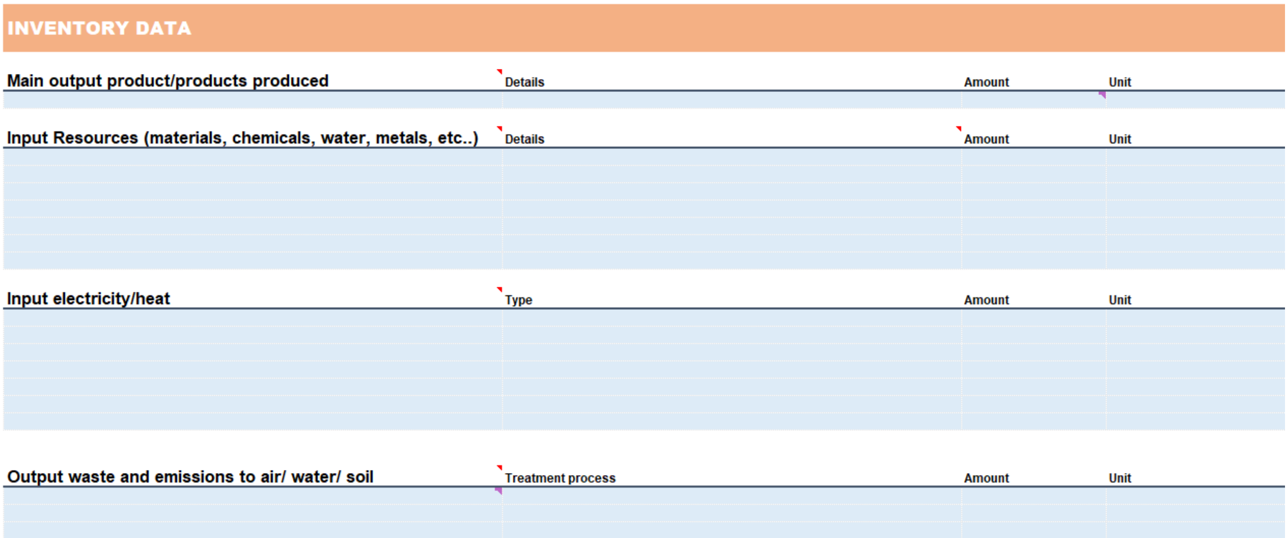


Figure 10 Example of the template used for primary data collection

For the foreground main processes, the manufacturing location was assumed to be China for the PV wafer, and Europe for the rest of the processes, to better represents the average location of the MC2.0 producers. While for the background processes, process consumables are assumed to be sourced globally, by using the general available "market data" on the Ecoinvent 3.9 database.

The PV laminate production – also referred as MC2.0 "front-end line" - and the BIPV roof tiles are based on primary data already available at TNO, that have been collected in previous projects. The TNO datasets are based on a production line for the CIGS production, and on application of a pilot mass customization line the integration into the rooftiles. For the c-Si PV cells, the secondary data from the source Müller et al., 2021[36] are used, which refer to Passivated Emitter Rear Cell (PERC) technology.

For the back-end integration line, that assembles the PV laminates into the various BIPV solutions, primary data were collected thanks to the partners: G2P, IWIN, SUPSI, SCHW, TNO.

The BOS is modelled from secondary data available from the IEA PVPS T12 LCI Report 2020[37], and the data of the inverter taken from the Ecoinvent, in accordance with most recent studies[38]. Due to the high difference in the impact results between the IEA PVPS inventory and the Ecoinvent database, the latter has been used in this analysis as a more conservative assumption. It should however be noted that an updated life cycle analysis of inverters is needed in order to obtain more reliable data. However, since all analysed systems use the selected inverter, it will not impact the comparison of the system.

To compare the results with the current mainstream c-Si PERC PV roof standard mounted technology, the inventory from Müller et al., 2021[36] was used as reference. To compare instead the BIPV results with traditional building elements i.e., without PV integrated, traditional façades, windows or roof tiles were

[36] Müller, A., Friedrich, L., Reichel, C., Herceg, S., Mittag, M., & Neuhaus, D. H. (2021). A Comparative Life Cycle Assessment of Silicon PV Modules: Impact of Module Design, Manufacturing Location and Inventory. Solar Energy Materials and Solar Cells, 230, 111277. Available at: https://doi.org/10.1016/j.solmat.2021.111277
[37] Frischknecht, R., Stolz, P., Krebs, L., de Wild-Scholten, M., Sinha, P., Fthenakis, V., Kim, H. C., Raugei, M., & Stucki, M. (2020). Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems. International Energy Agency (IEA) PVPS Task 12, Report T12-19:2020.
[38] Van der Hulst, M. K., Adrianto, L. R., Tokaya, J. P., Arvidsson, R., Blanco Rocha, C. F., Caldeira, C., & Hauck, M. (2024). How can LCA include prospective elements to assess emerging technologies and system transitions? The International Journal of Life Cycle Assessment, 26(8), 1541-1544. Available at: https://doi.org/10.1007/s11367-021-01934-w

modelled based on secondary data from EPDs, literature or the Ecoinvent 3.9 database, to represent the majority of EU buildings.

To model the prospective LCA, the background inventory was modified according to two scenarios, from 2020 until 2050, that here will be called as: "worst case" and "best case". Both scenarios were developed using the REMIND model[39]. The "worst case" scenario represents the "SSP2 – Middle of the road – Base", while the "best case" scenario represents the "SSP2-Middle of the road – PkBud500", as in Table 6.

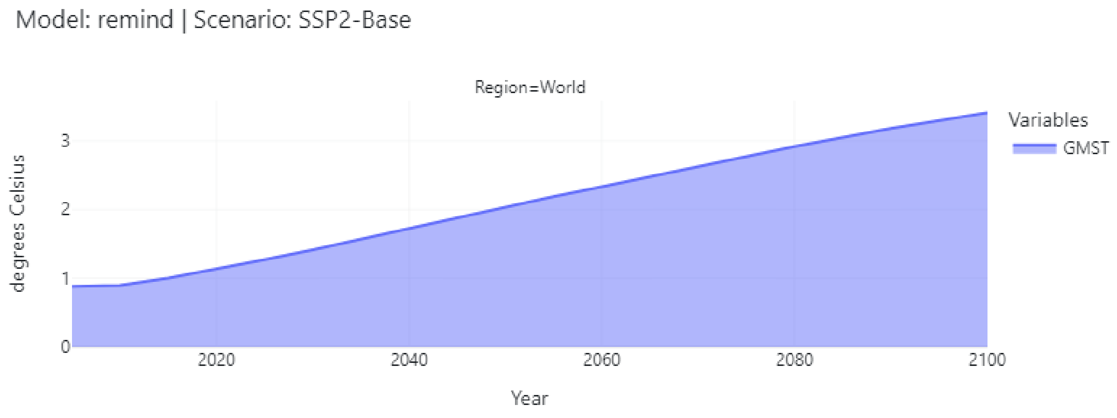
Table 6 Description of the best case and worst-case scenarios adopted in the prospective LCA for the present study

Cases	Model	Socio economic pathway (SSP) associated	SSP description	Scenario associated	Description	Years analyzed
Worst case	REMIND	SSP2-Middle of the road	Continuation of current trends, with some progress towards achieving development goals	Base	Emissions continue to grow at the same rate as in the past	2020, 2030, 2050
Best case	REMIND	SSP2 – Middle of the road	Continuation of current trends, with some progress towards achieving development goals	Peak Budget 500 $GtCO_2$	66% chance of limiting global warming to 1.5°C above pre-industrial levels	2030, 2050

The common assumption for both scenario is the "SSP2 – Middle of the road" model, which describes a market path in which social, economic, and technological trends do not shift markedly from historical patterns. It represents a continuation of current trends, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. The "Base" additional assumption represents a scenario where emissions continue to grow at the same rate as in the past, while the "Peak Budget 500 $GtCO_2$ (PkBudg500)" represents a situation where cumulative emissions are limited to 500 $GtCO_2$, resulting in a 66% chance of limiting global warming to 1.5°C above pre-industrial levels. The global mean surface temperature anomaly relative to 1850-1900 for both paths is illustrated in Figure 11. To implement the selected scenarios in the prospective LCA, the background inventories were downloaded from the Activity Browser software, for the year 2020 (only Base), 2030 and 2050[40].

[39] Potsdam Institute for Climate Impact Research (PIK). (2024). REMIND (REgional Model of INvestments and Development). PIK. Available at: https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind

Worst case:



Best case:

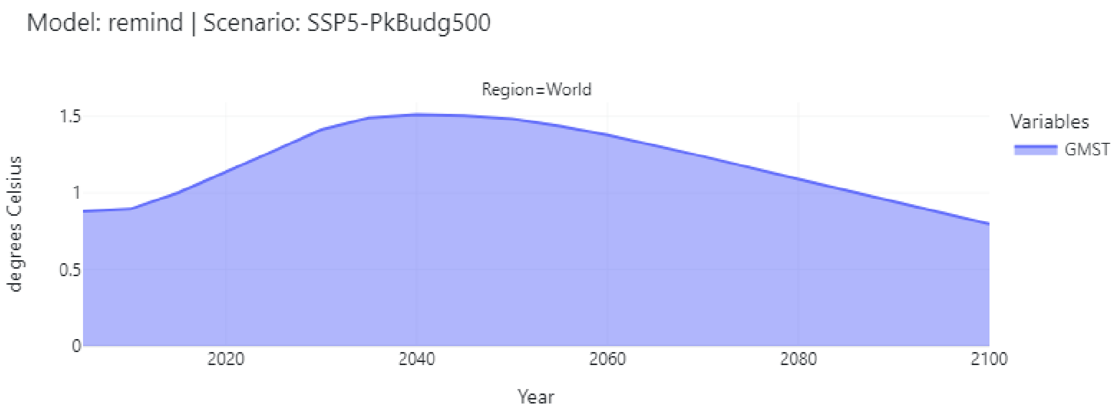


Figure 11 Illustration of Global mean surface temperature (GMST) anomaly relative to 1850-1900, according to the selected scenarios[40]. Top plot: worst case, Bottom plot: best case.

[40] Premise Dashboard. (2024). Premise Dashboard. Available at: https://premisedash-6f5a0259c487.herokuapp.com/

4 Life Cycle Impact Assessment

4.1.1 CASE 1: PV LAMINATE LEVEL

The first step of the current life cycle impact assessment is the evaluation of the PV laminate impact, made with c-Si and CIGS PV cells. In Table 7, the characteristics of the laminates are illustrated. In this report, the PV laminate is assumed to be a common part for all the five IPV products. All additional frontsheets or backsheets specific for the different products, are included in the CASE 2 of this analysis, inside the building element components. The manufacturing location has been selected to better represent the MC2.0 project location, as described in the previous chapter.

Since the integration material for the PV laminate can be made with either a glass or polymeric frontsheet, a sensitivity analysis has been included for the integration material, evaluating both the CIGS and the c-Si PV laminates with a glass-based frontsheet, and with a polymeric ETFE-based frontsheet.

Table 7 Description of the components and sourced used to model the common PV laminate in this study. *For the integration materials of the c-Si PV laminate, a sensitivity analysis has been included, evaluating not only the glass-based frontsheet, but also a polymeric ETFE frontsheet – same as for the CIGS based PV laminate.

COMPONENT	CIGS LAMINATE	MANUFACTURING LOCATION	SOURCE
PV CELL	• Mo back contact • CIGS absorber • CdS buffer • ZnO/ITO front contact	Europe	TNO primary data
CELL METALLIZATION	• Cell metallization • Diodes	Europe	TNO primary data
LAMINATE INTEGRATION	• PO encapsulant • Al/PET backsheet • PET/ETFE frontsheet • Sealants • PMMA adhesive (proxy for PSA)	Europe	TNO primary data
COMPONENT	**c-Si LAMINATE**	**MANUFACTURING LOCATION**	**SOURCE**
PV CELL	• PERC PV cell	China	Müller et al., 2021
CELL METALLIZATION	• Cell metallization • Diodes	Europe	Müller et al., 2021
LAMINATE INTEGRATION	• EVA encapsulant • Glass frontsheet • PET backsheet • PMMA adhesive • Sealants	Europe	Müller et al., 2021

The impact assessment results of the PV laminates are presented in Figure 12 for 1 square meter of PV laminate. Here, the EF 3.1 impact indicators have been aggregated in a single score, following the EF 3.1

weighting and normalizing methodology. From this result, it is possible to observe how the overall environmental impact of the CIGS cell is significantly lower than the c-Si.

The minerals and metals resources depletion impact category has the highest share for both the technologies, followed by the climate change impact. For both PV laminates are the fossil energy resources, eutrophication and ecotoxicity of freshwater also relevant. For the CIGS laminate, the ozone depletion category has a relevant share due to the ETFE frontsheet, while for the c-Si the particulate matter impact category has a visible contribution.

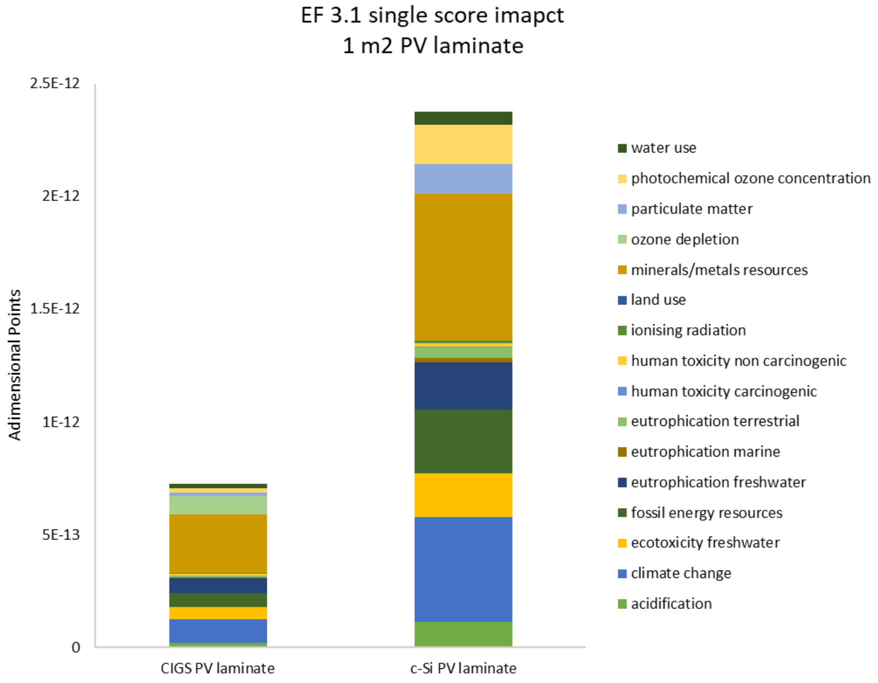


Figure 12 Normalized and weighted Environmental Footprint 3.1 impact in single score, for 1 square meter of PV laminate.

To better understand which PV laminate's component is more responsible for each impact category, some of the EF 3.1 impact categories are normalized, weighted, and plotted to show the contribution to each component, in Figure 13.

The c-Si PV cell has the highest impact on the climate change impact category due to the crystalline silicon wafer production, which is an energy intensive process. In this study, the wafer was modelled using the Chinese electricity mix, which is 62% coal-based in 2022 according to IEA[41]. Therefore, the supply of the wafer from different manufacturers which makes use of high amount of renewable energy in their process could improve substantially the sustainability of the c-Si PV laminate.

For the CIGS PV laminate, the integration material has the highest impact contribution in the climate change impact category, mainly due to the ETFE frontsheet.

The higher impact of the c-Si in the materials resources category is due to the production of flat glass, mainly due to the soda ash. Finally, for the ozone depletion, the high impact of CIGS laminate is due to the ETFE, which is about 40 times higher than the c-Si PV with glass frontsheet.

[41] International Energy Agency (IEA). (2024). China: Energy Mix. IEA. Available at: https://www.iea.org/countries/china/energy-mix

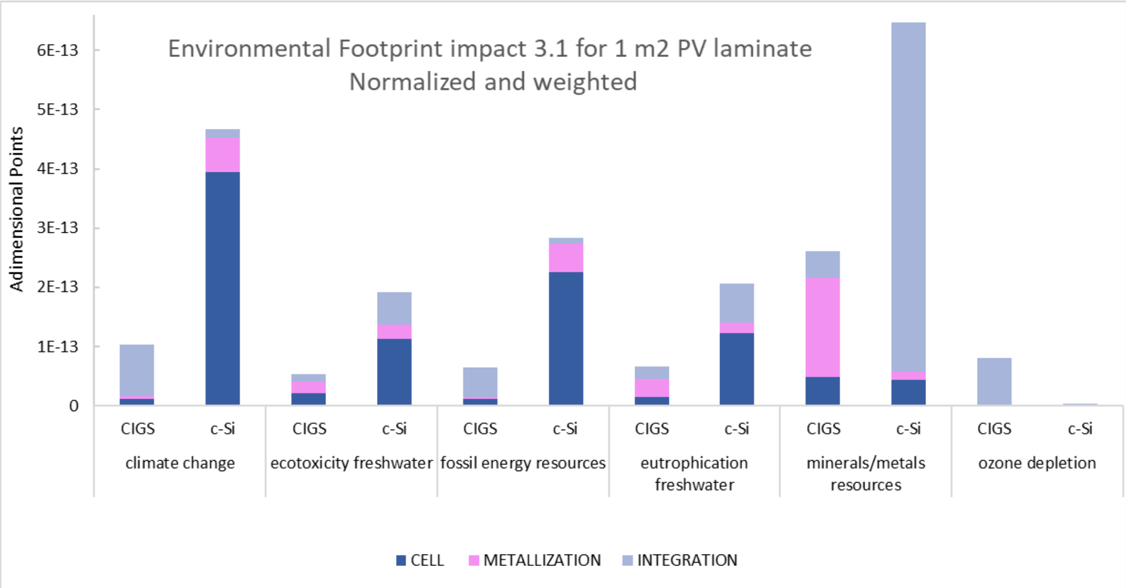


Figure 13 Environmental Footprint 3.1 impact for 1 square meter of PV laminate, normalized and weighted in adimensional points, showing the contribution to each impact category.

As discussed before, since the PV laminate frontsheet can be either glass or polymer based, we performed a sensitivity analysis of the impact of each option on the overall impacts. The results are shown in Figure 14. Here, the lighter colours represent the results for the glass frontsheet and the darker colours for the polymer frontsheet. Here, we can observe how the impacts for climate change, material resources and ozone depletion are much lower for the glass frontsheet compared to the ETFE frontsheet. For the other impact categories, there is not a big difference between glass and polymeric frontsheet. Research is currently ongoing at TNO, to replace the ETFE based material with an eco-friendlier one.

For both types of frontsheets, the impact of the CIGS laminate is significantly lower than that of the c-Si laminate, for all the impact categories except the ozone depletion one.

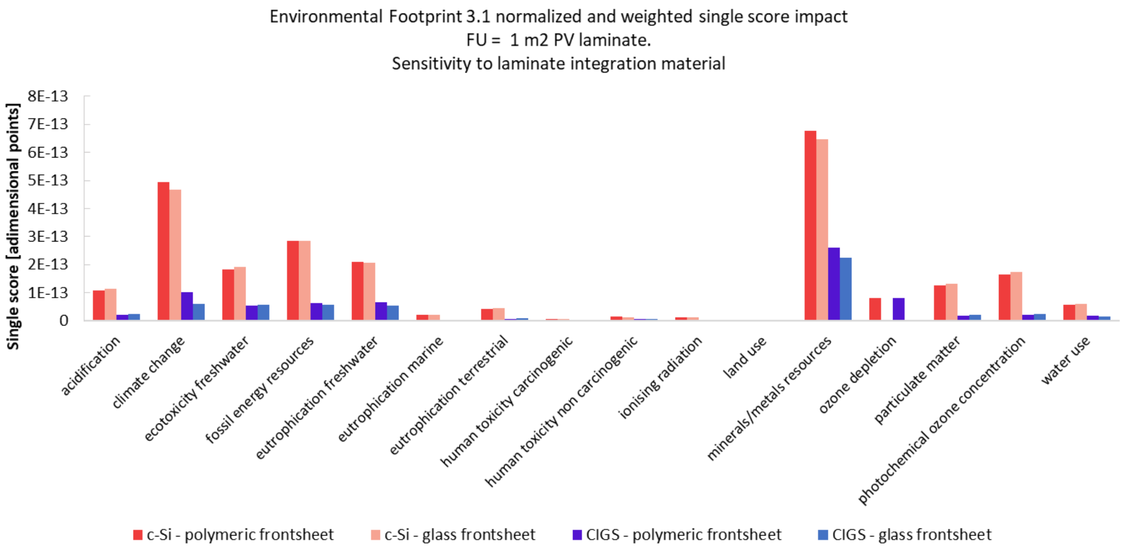


Figure 14 Environmental Footprint 3.1 impact for 1 square meter of CIGS (blue) and c-Si (red) PV laminate, integrated with a glass frontsheet (light colour) or with a ETFE polymer-based frontsheet (dark colours). The impact is normalized and weighted using the EF 3.1 normalization and weighting factors.

In the following steps, the CIGS-based laminate will be modelled with an ETFE frontsheet, and the c-Si laminate will be modelled with a glass frontsheet, to better reflect the state of the art.

4.1.2 CASE 2: BIPV PRODUCT

In this section, the focus is shifted from the PV laminate only, to the PV laminate integrated into the BIPV product. Here, the cradle-to-gate environmental impact is evaluated, measured with the EF 3.1 method, normalized and weighted according to the same methodology. The functional unit is the square meter of different BIPV products, without including the BOS.

In Figure 15, the single score EF impact is illustrated, from which it is possible to see that the minerals and metals material resources depletion category is the greatest, followed by the climate change category.

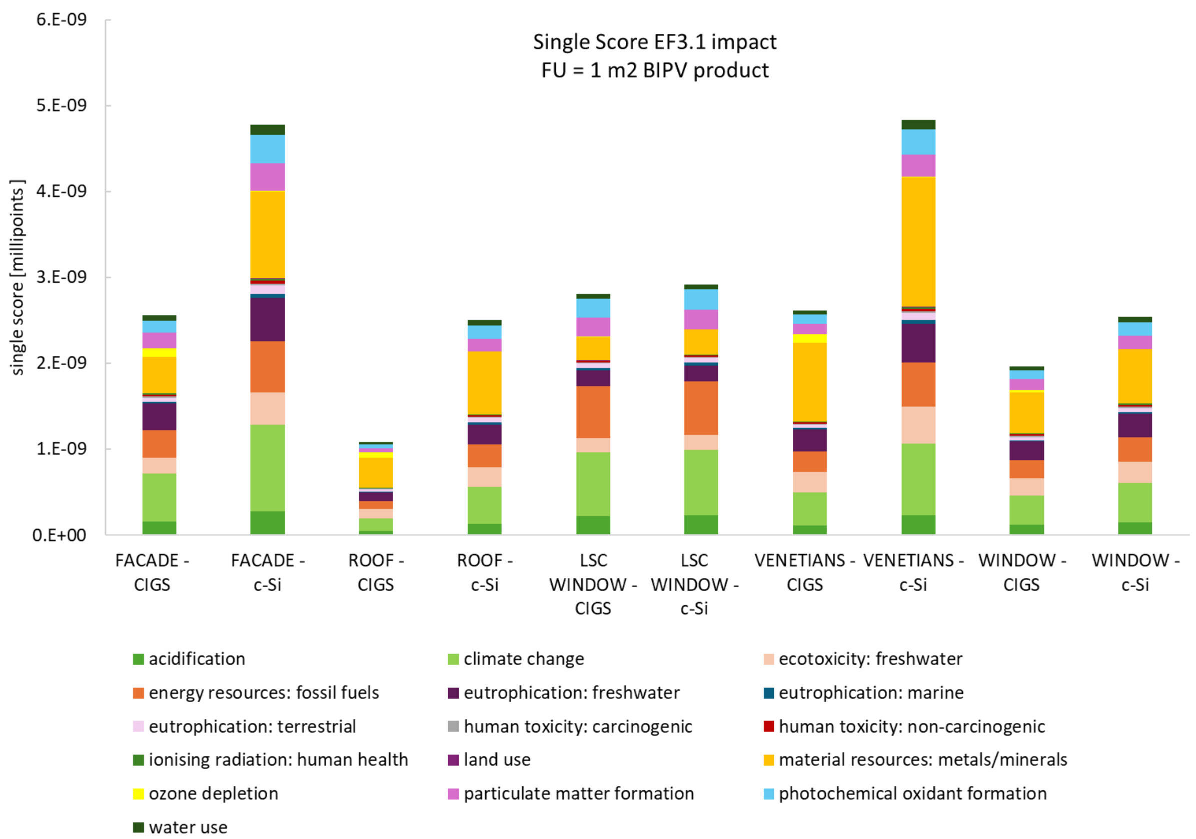


Figure 15 Normalized and weighted single score EF 3.1 impact of different BIPV technologies, for 1 square meter of BIPV, expressed in millipoints

To understand which component is contributing the most to the impacts, the most important categories have been analysed in more detail. Figures from Figure 16Figure 20 illustrates the environmental impact for the most relevant indicators, selected based on the results of the single score impact. The results for all the other indicators are available in ANNEX 1. The highlights resulted from this analysis, for each type of product, are the following:

- For the façade BIPV, the aluminium cassette has the most relevant contribution share for almost all the categories, while for the roof tile the major contributor is the PV laminate.
- For the LSC window BIPV, the PMMA slab production has the highest share, and this element is also the reason why the impact of this BIPV type is higher than the others. The PV laminate has an overall low impact contribution, due to the low area coverage.
- For the venetian window BIPV, the PV laminate and the IGU, mainly due to the glass production, are in general the most relevant contributor to almost all the categories, except for the minerals and metals material resources, where the major responsible is the electronic motor for the blinds.
- For the window with PV frame, the IGU production or the aluminium components are the major contributors for almost all the categories. The PV laminate has here an overall low impact contribution, due to the low area coverage.

1. FAÇADE BIPV

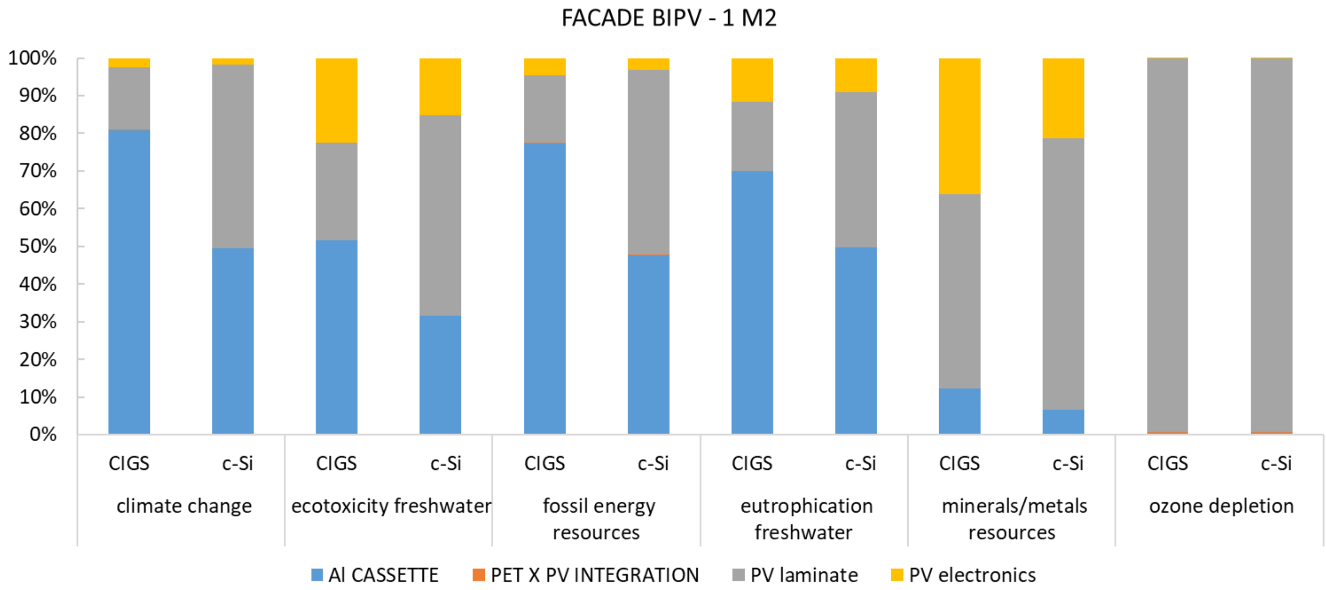


Figure 16 Impact contribution to 1 square meter of façade BIPV with CIGS PV laminates and c-Si PV laminates, considering several EF3.1 impact categories.

2. ROOF TILE BIPV

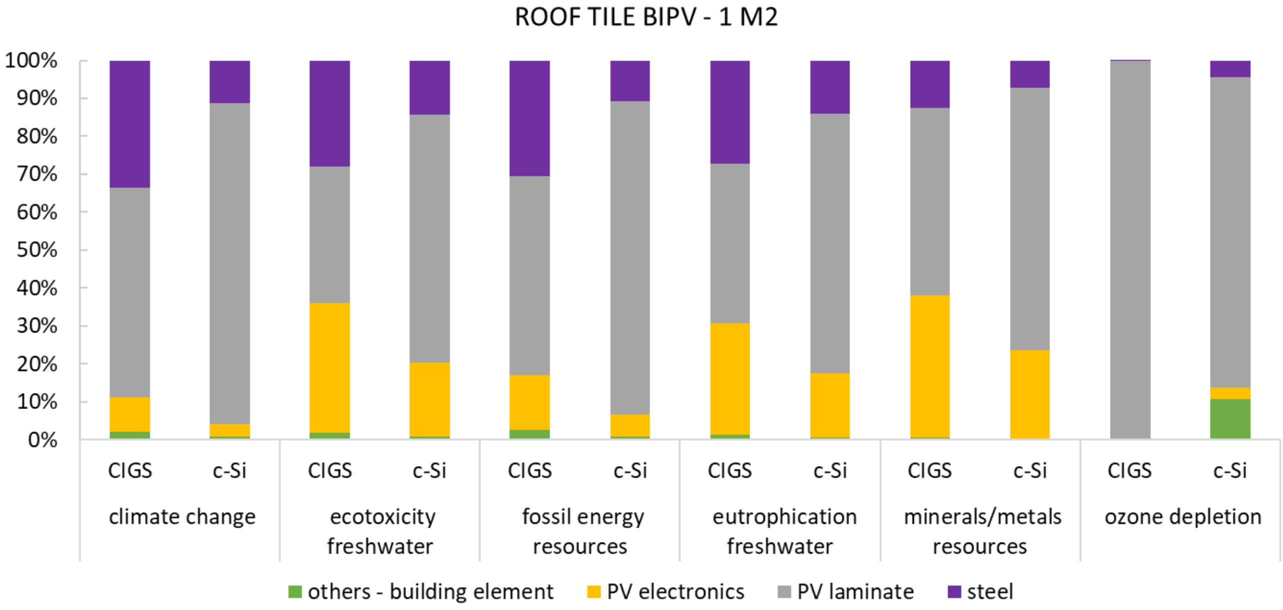


Figure 17 Impact contribution to 1 square meter of roof tile BIPV with CIGS PV laminates and c-Si PV laminates, considering several EF3.1 impact categories.

3. LSC WINDOW BIPV

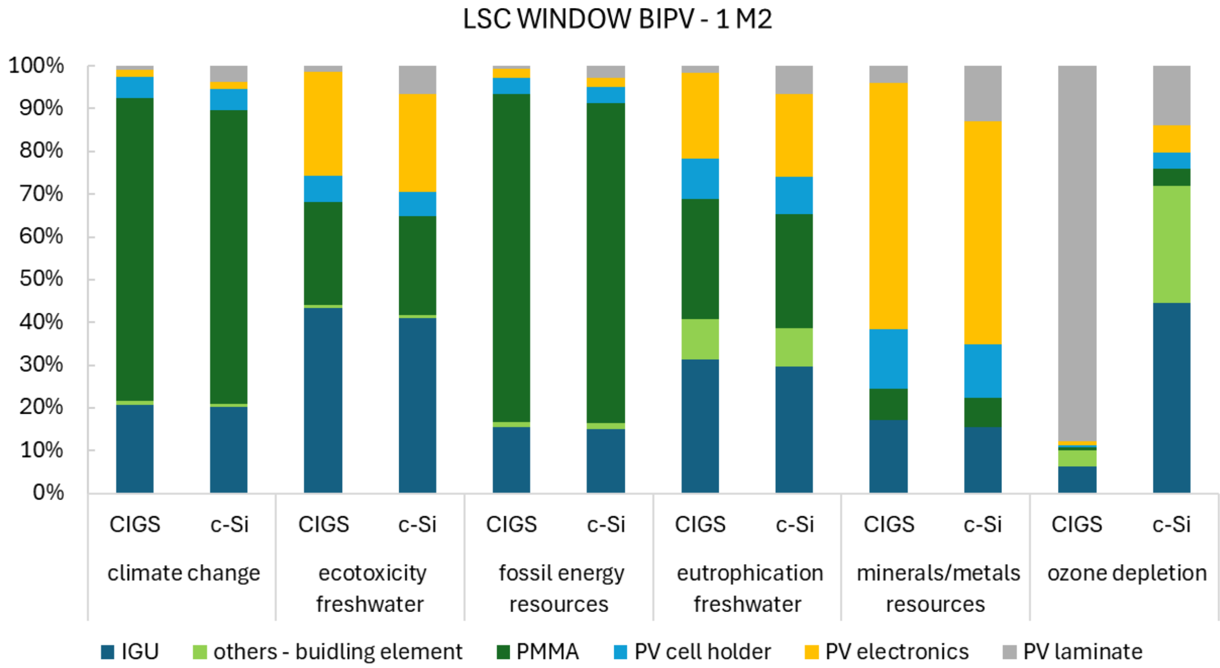


Figure 18 Impact contribution to 1 square meter of window with LSC window BIPV with CIGS PV laminates and c-Si PV laminates, considering selected EF3.1 impact categories.

4. VENETIAN WINDOW BIPV

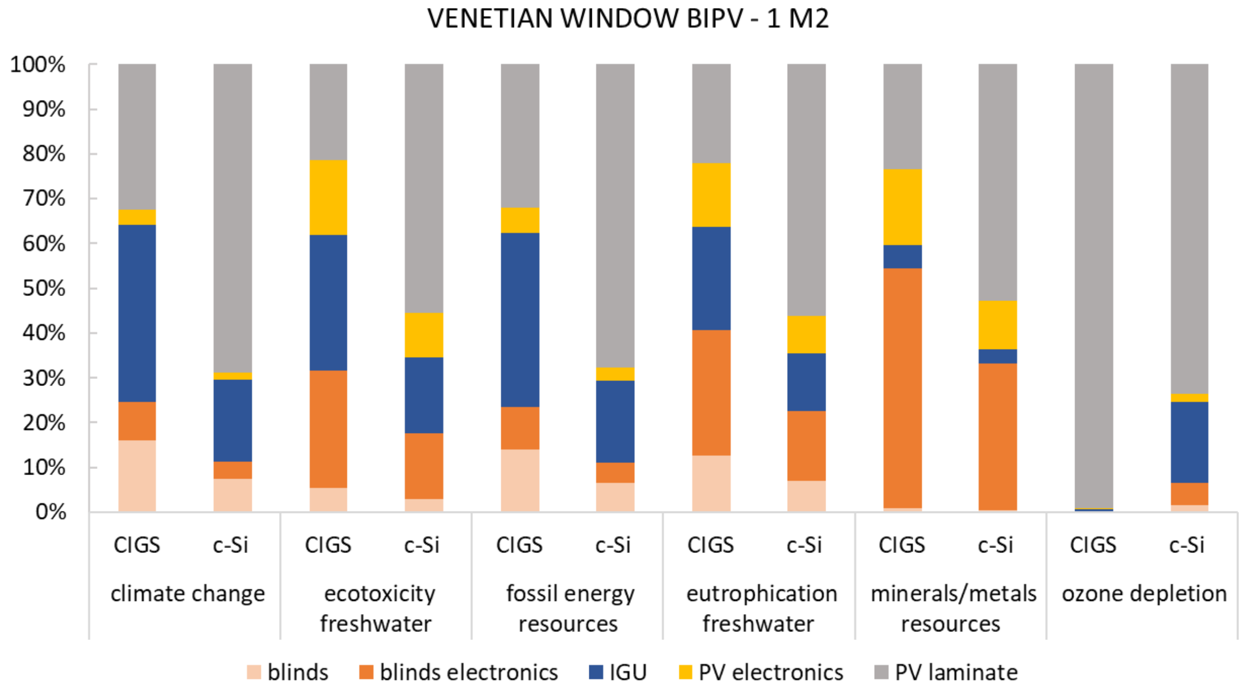


Figure 19 Impact contribution to 1 square meter of venetian window BIPV with CIGS PV laminates and c-Si PV laminates, considering selected EF3.1 impact categories

5. WINDOW WITH PV FRAME BIPV

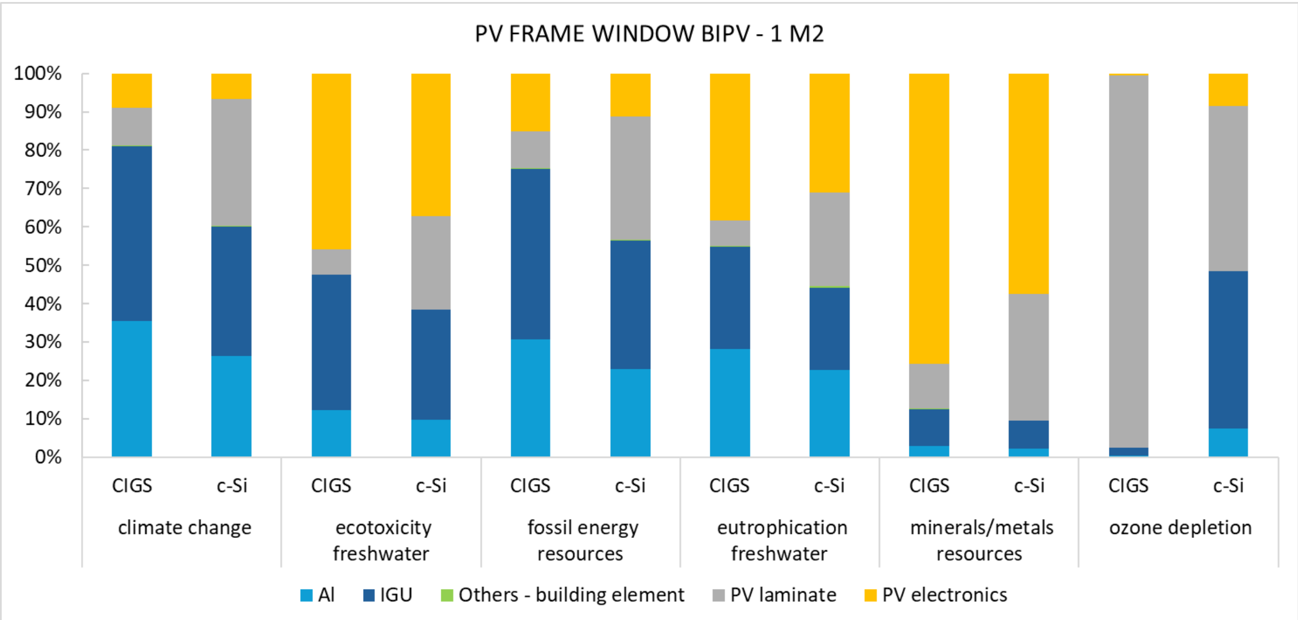


Figure 20 Impact contribution to 1 square meter of PV frame window BIPV with CIGS PV laminates and c-Si PV laminates, considering selected EF3.1 impact categories.

4.1.3 CASE 3: BIPV SYSTEM INTEGRATION

The focus of the third case is the entire BIPV system, with the addition of the balance of system (BOS) to the BIPV products. Here, the BOS includes a 2.5 kW inverter and all the electronic materials including cables, fuse boxes and lightning protection. The functional unit has been converted from square meter of BIPV to kWp of installed capacity by using the best estimated values for the BIPV efficiencies, expressed in kWp per square meter, as better explained in Section 2.2. Since the products are not yet available commercially, the values of the efficiencies are not the final ones but estimated values, therefore a sensitivity analysis was performed considering the BIPV efficiency as a parameter. The sensitivity analysis results for the climate change impact are presented in this section, in Figure 25.

The single score EF 3.1 results for 1 kWp of BIPV installed capacity, considering the different efficiency of the products and compared it to the standard roof mounted PERC PV module, is illustrated in Figure 21.

From this figure it is also possible to observe how the LSC window BIPV has a higher impact, both the one with CIGS and c-Si PV laminate. This is due to the fact that the PMMA slab has a very high impact for this type of products, as was highlighted in detail in Figure 18, but also because the BIPV module efficiency is low compared to the other products. Also the PV frame window presents a slightly higher impact than the rest of the PV modules, because of its lower efficiency.

It is important to notice, that these two products belong to a different category compared to the others, since they are transparent products, which accounts for their lower efficiency. The LSC window BIPV product is even more experimental and innovative, as the photovoltaic cells placed inside the window frame rely on light that is scattered through the LSC nanoparticles, resulting in higher losses.

Compared to the single score impact of the BIPV modules, without BOS, here it is evident how the metals and minerals material resources category has a greater contribution (yellow). As the next graphs will explain in more detail, this is due to the production of the electronic components in the BOS.

From this figure it is also possible to observe how the LSC window BIPV has a higher impact, both the one with CIGS and c-Si PV laminate. This is due to the fact that the PMMA slab has a very high impact for this type of products, as was highlighted in detail in Figure 18, but also because the BIPV module efficiency is low compared to the other products. Also the PV frame window presents a slightly higher impact than the rest of the PV modules, because of its lower efficiency.

It is important to notice, that these two products belong to a different category compared to the others, since they are transparent products, which accounts for their lower efficiency. The LSC window BIPV product is even more experimental and innovative, as the photovoltaic cells placed inside the window frame rely on light that is scattered through the LSC nanoparticles, resulting in higher losses.

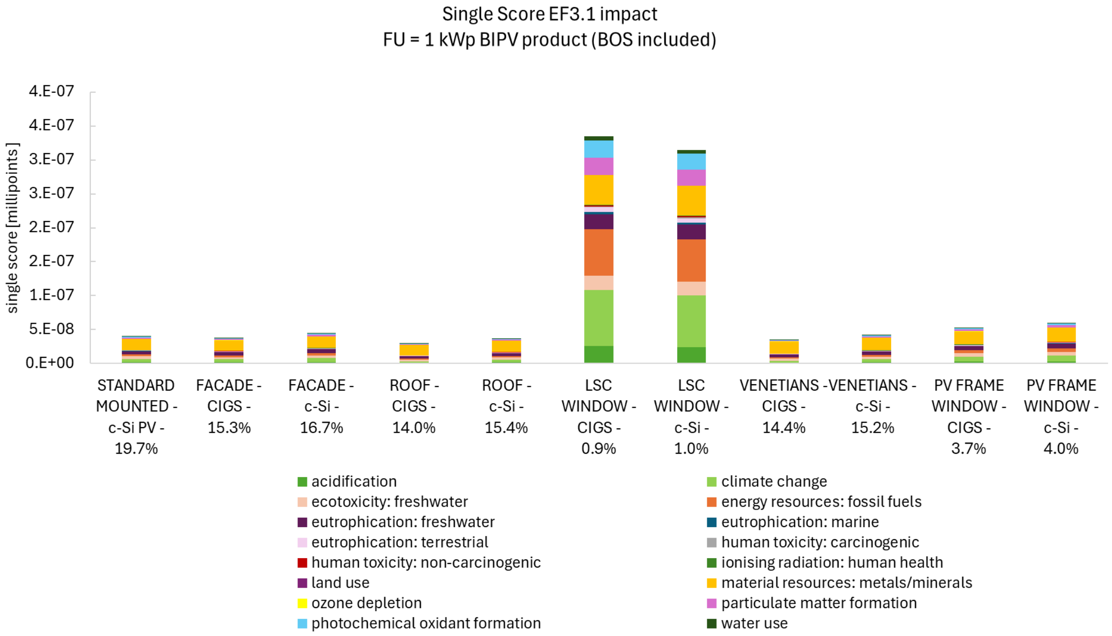


Figure 21 Normalized and weighted single score EF 3.1 impact of different BIPV technologies, for 1 kWp of BIPV system installed, expressed in millipoints. This graph is made considering the estimated efficiency in Table 3.

In Figure 22 we can observe how the BOS is the major cause of impact in the category of minerals and metals material resources depletion. This is mainly due to the high amount of copper required for manufacturing the inverter. Figure 23 furthermore shows how the BOS is also the major cause of the impact of freshwater eutrophication, again mainly due to the production of the inverter. For the impact in the category climate change however, we show in Figure 24 that either the PV laminate or the building element are the major cause of impact.

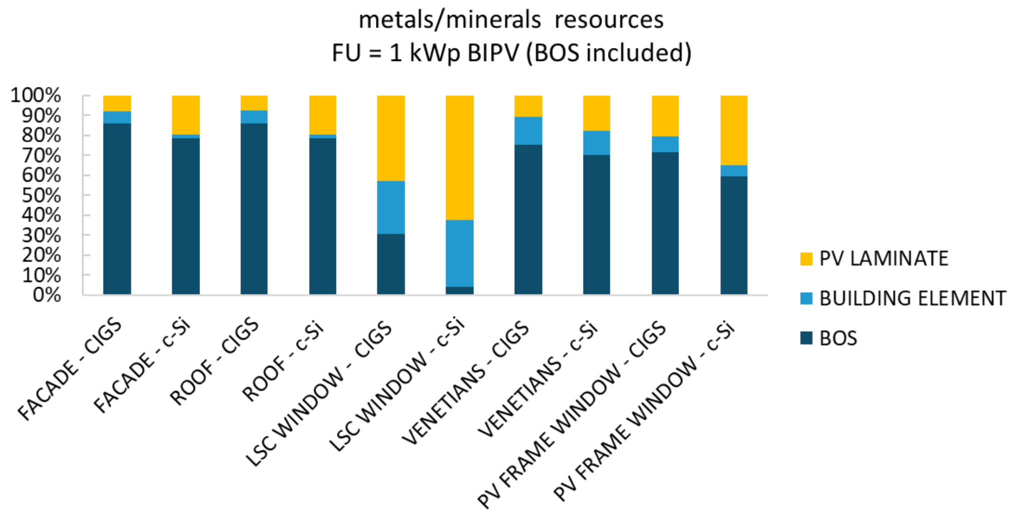


Figure 22 Environmental impact in the category metals/minerals resources depletion, showing the contribution of the different BIPV products, cradle-to-gate and BOS included, for 1 kWp of installed capacity, using the estimated efficiency.

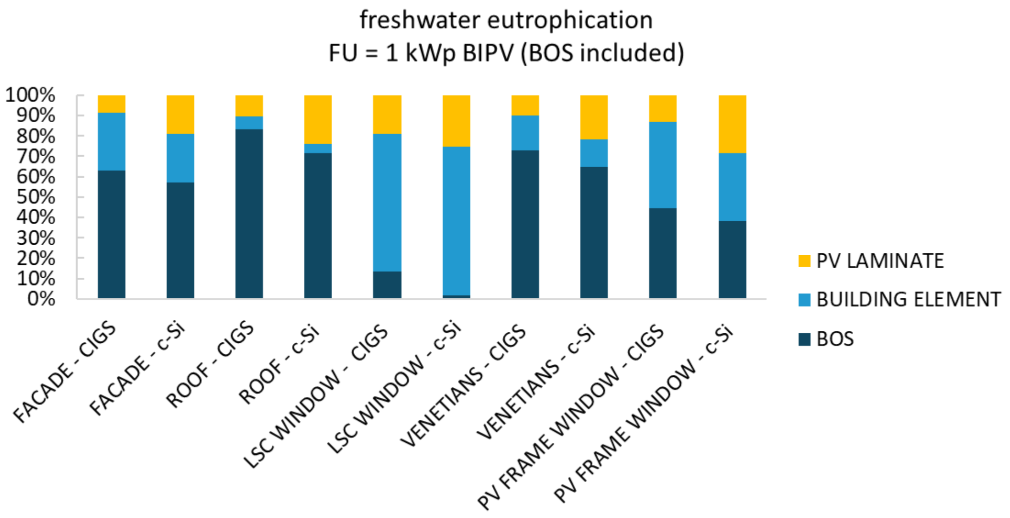


Figure 23 Environmental impact in the category freshwater eutrophication, showing the contribution of the different BIPV products, cradle-to-gate and BOS included, for 1 kWp of installed capacity, using the estimated efficiency.

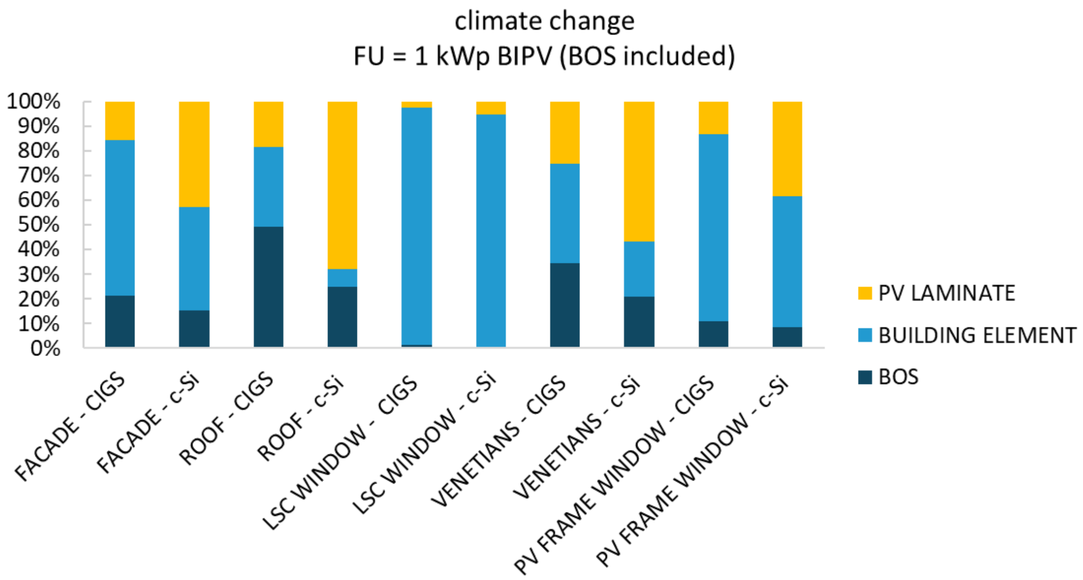
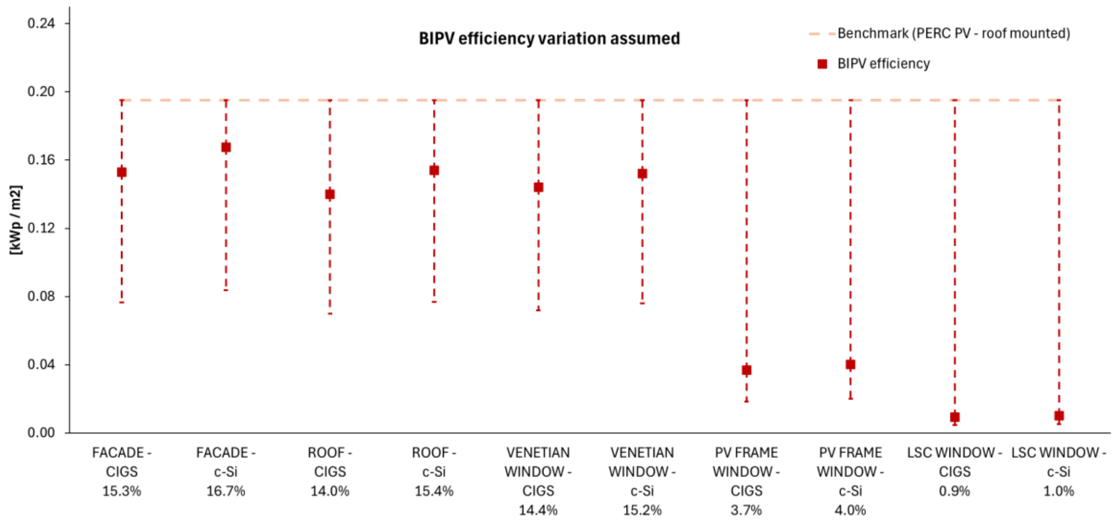


Figure 24 Environmental impact in the category climate change, showing the contribution of the different BIPV products, cradle-to-gate and BOS included, for 1 kWp of installed capacity, using the estimated efficiency.

Since all the products are still in the characterization phase within the time of this report, the efficiency used for the conversion in kWp, represents a best estimation of the final values. Because of this uncertainty, a sensitivity analysis has been performed, and the results for the climate change impact category are visualized in Figure 25. Here, a reasonable deviation of the estimated efficiency is assumed, considering the benchmark value of the PERC roof mounted PV as maximum upper limit, and a reduction of 50% respect the best estimated value as lower limit. As a result, it is possible to observe how the final GHG emissions per kWp of installed capacity are strongly affected by the BIPV efficiency, and if the efficiency is halved, the GHG emissions can arrive way above the benchmark value of the PERC roof mounted PV (orange dashed line).

a)



b)

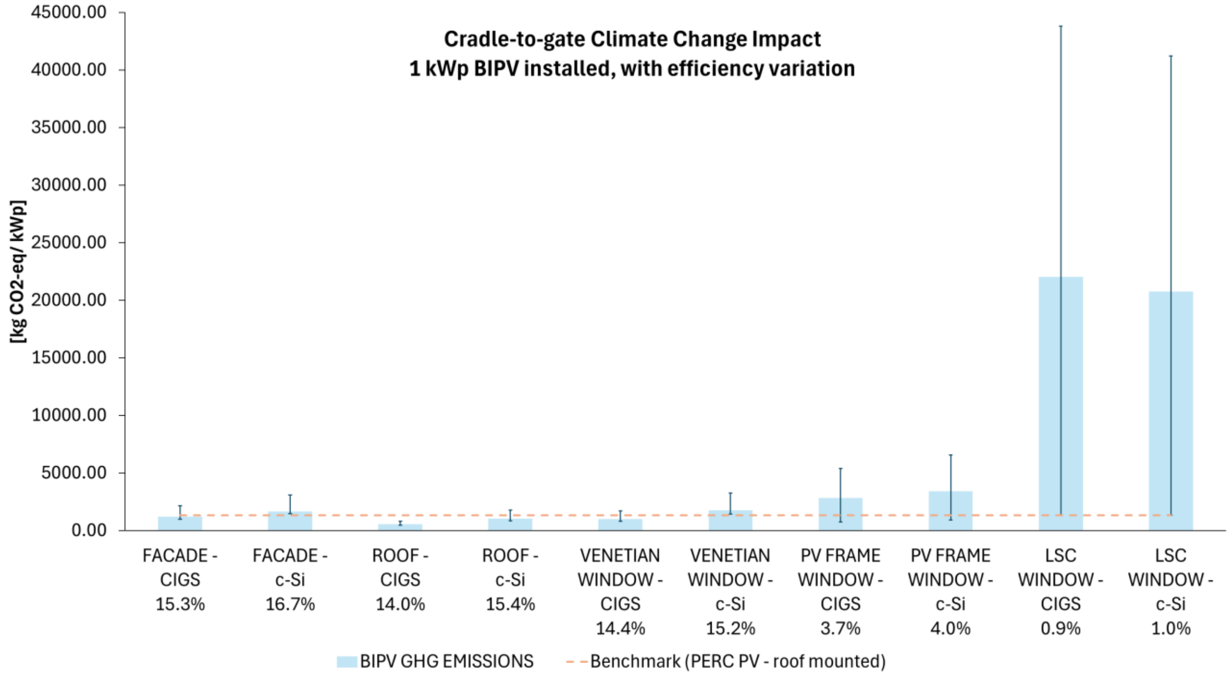


Figure 25 In Figure (a) variation of the BIPV efficiency assumed from the best estimated efficiency (red square): the upper limit is the benchmark PERC roof mounted PV value, and the lower value is an assumed 50% reduction compared to the best estimated efficiency. In Figure (b) climate change impact for 1 kWp of BIPV, for the different technologies, cradle-to-gate, including the BOS. The error bars represent the results in the GHG emissions due to the variation in the BIPV efficiency. The horizontal orange dashed line represents the GHG emissions of a standard roof mounted c-Si PV, as a benchmark comparison.

Continuing with the focus on the climate change impact category, the second objective of this case study is to compare the BIPV products with a traditional building. Since no guidelines are available to perform this type of analysis, the results are here evaluated both for a square meter functional unit, and for a kWh of electricity generated.

When using the square meter functional unit, the BIPV have been compared with traditional building envelope elements, selected with feedback from the MC2.0 BIPV producers, as follows:

- Windows BIPV are compared with traditional IGU windows with/without venetians
- Façade BIPV with clay brick façade
- Roof tile BIPV with clay roof tile.

On the other hand, when using the kWh as functional unit, the solar electricity generated with the BIPV products is compared with the electricity consumed from the grid of selected installation locations. Here, we have selected Athens and Oslo as an example of two very different locations, following the results of the Virtuani et al. 2023[20] study. To perform this calculation, the climate change impact was converted from kWp to kWh using the total electricity yield produced by the BIPV products within a 30-year lifetime, considering the selected locations, orientations and adjusting the tilt depending on the BIPV type. More details on the assumption considered to convert the impact in kWh are explained in Section 2.2.

As shown in

Figure 26, the cradle-to-gate results show that the climate change impact of all the BIPV products is higher than the one of a traditional building, for 1 square meter of building element. Of course, this is to be expected as the traditional building has no functionality of generating electricity.

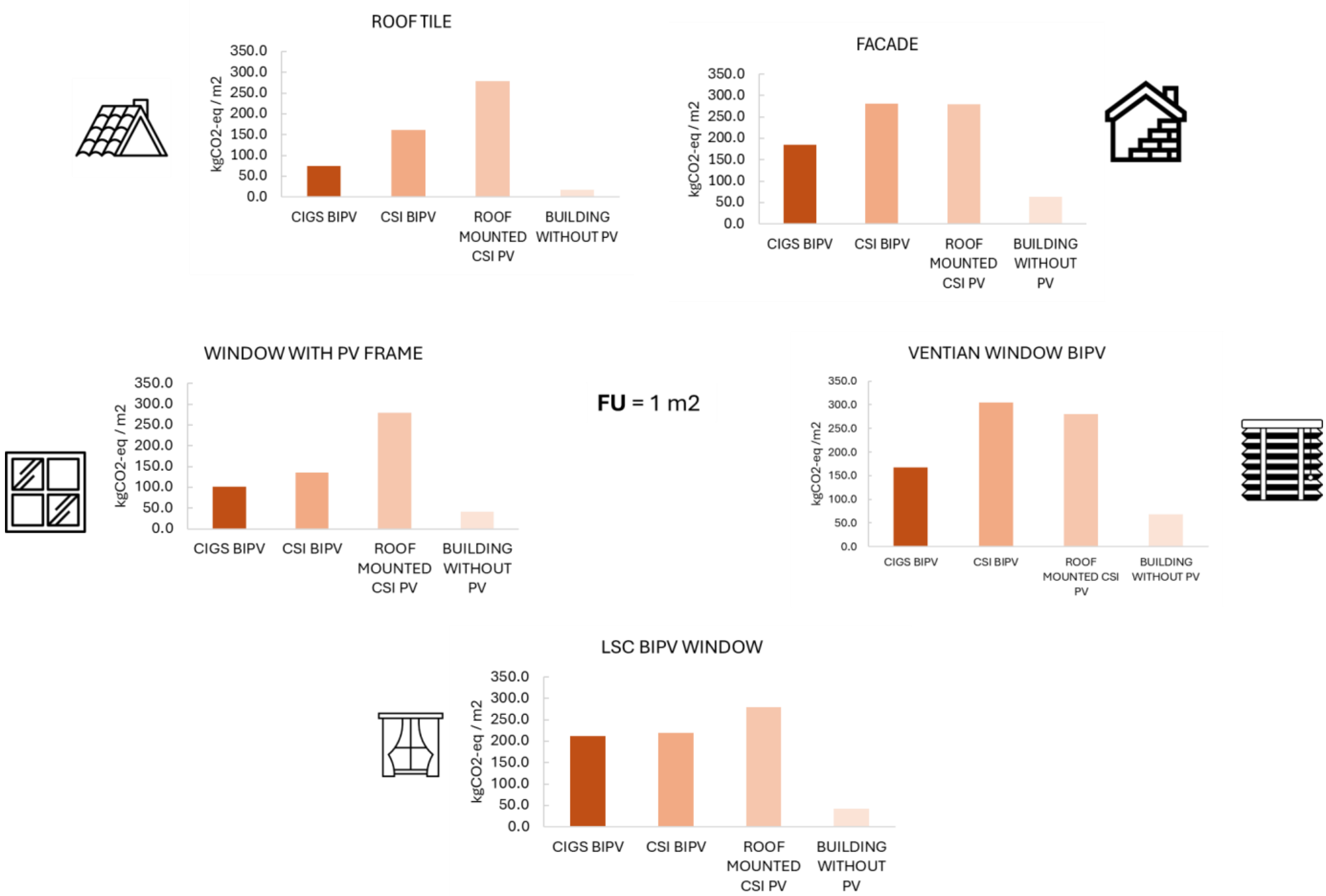


Figure 26 GHG emissions per square meter of BIPV system, for different BIPV products, BOS included. Comparison with a traditional building envelope and with a traditional roof mounted c-Si PV.

Hence, in the following figures we show the results for electricity generation from the BIPV products compared to the electricity consumed from the local grid. Figure 27 shows that the GHG emissions of electricity generated with the BIPV products when installed in Athens, facing south, are significantly lower compared to the GHG emissions of electricity from the local grid (2022 data, see Section 2.2).

For this step of the analysis, among the window BIPV products, only the window with PV venetians and the window with PV frame were included. The LSC BIPV window was excluded since the GHG emissions associated to this product are way higher compared to the benchmark (see Figure 25), due to the peculiarity of the product as explained in Section 2.2, that needs to be considered in a separate category.

Although there is variation in the GHG emissions per kWh between the BIPV products, all of them show much lower impacts compared to electricity from the local grid.

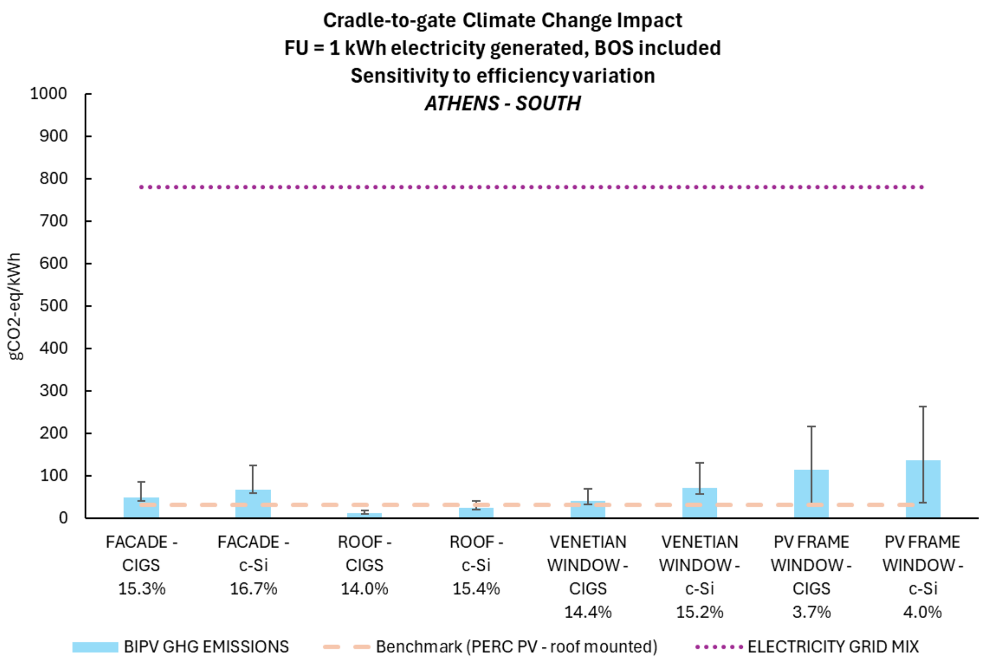


Figure 27 Climate change impact for 1 kWh of electricity generated from south oriented BIPV, with error bars representing the sensitivity to efficiency variation, standard roof mounted PERC PV (dashed orange line), or from the Athens grid mix (dashed purple line).

A sensitivity analysis has been performed to evaluate the effect of a different installation location and orientation; the results are represented by the error bars to the graphs of Figures Figure 27-Figure 29. If the BIPV products are assumed to be installed facing north, in the worst possible orientation, the production of 1 kWh of electricity from these BIPV products still has a much lower impact in terms of GHG emission compared to the electricity mix consumed from Athens' grid. Only for the LSC window this might not apply if its efficiency turns out to be on the lower end of the range investigated in our sensitivity analysis. As expected, in both north and south orientations, the vertical BIPVs – windows and façades - have a higher level of GHG emissions compared to the optimal oriented standard mounted PV and PV integrated roof tiles.

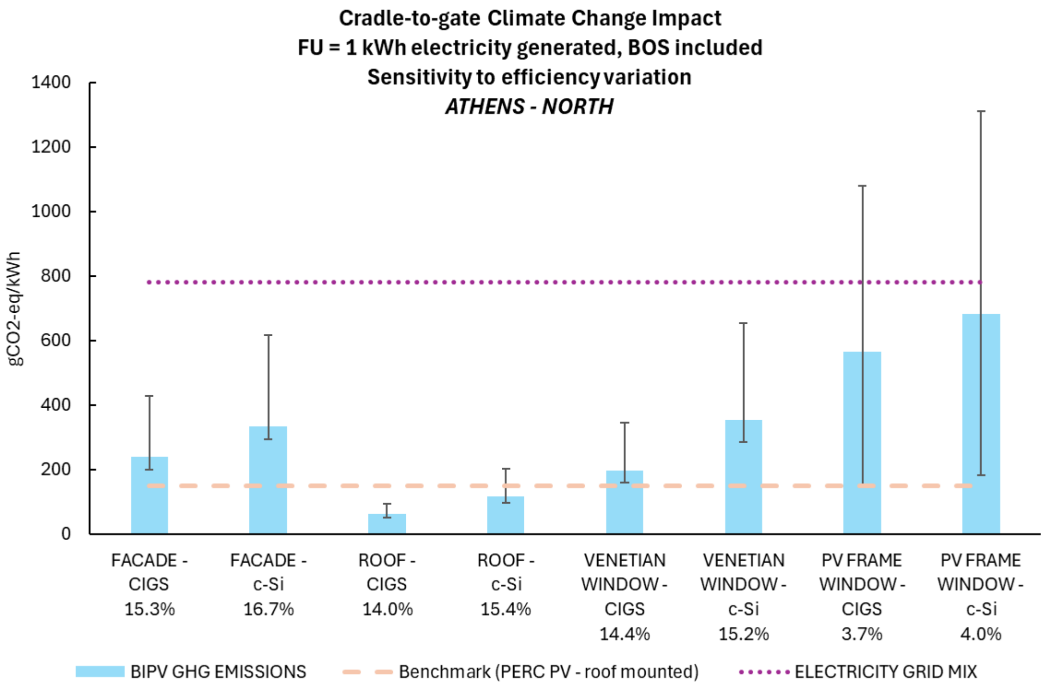


Figure 28 Climate change impact for 1 kWh of electricity generated from north oriented BIPV installed in Athens, with error bars representing the sensitivity to efficiency variation, standard roof mounted PERC PV (dashed orange line), or from the Athens grid mix (dashed purple line)

On the other hand, if the installation location is shifted to a location with an almost fully renewable electric grid, such as Oslo the advantage of the electricity generated with BIPV compared to that from the local grid is lost and the electricity coming from PV mounted or BIPV, is not competitive anymore with Oslo's country grid mix (data from 2022). The BIPV products' electricity generation would only have lower GHG emissions compared to a highly renewable-based grid, if they would be produced with renewable energy.

Considering that the carbon intensity of the European grid mix is 210 g CO_2-eq/kWh[42], the electricity generated with BIPV is still competitive with the average European grid mix when installed with a south orientation, and close to competitiveness if installed facing north.

[42] European Environment Agency (EEA). (2024). Greenhouse Gas Emission Intensity of Electricity Generation in Europe. Available at: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1

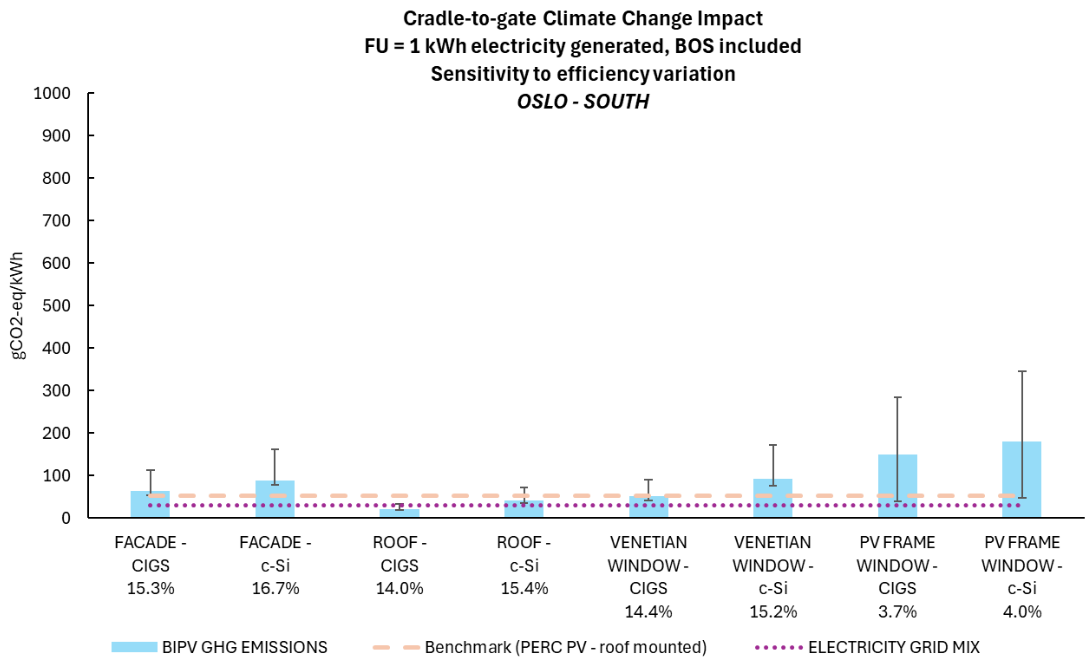


Figure 29 Climate change impact for 1 kWh of electricity generated from south oriented BIPV installed in Oslo, with error bars representing the sensitivity to efficiency variation, standard roof mounted PV (dashed orange line), and from the Oslo grid mix (dashed purple line).

For a more detailed analysis of the competitiveness of BIPV systems over the grid mix electricity, a deeper analysis is necessary, considering the specific building needs and hourly consumption profiles, the surface available for BIPV, real shading conditions and building façade orientation. Part of this analysis will be performed within WP3, in which the obtained carbon intensity of the MC2.0 BIPV solutions were inserted in a tool developed by EURAC, to optimize the optimal BIPV surface based on cost, carbon intensity and electricity generation. More detail on this type of optimisation are available in the MC2.0 Deliverable 3.4.

4.1.4 CASE 4: RECYCLING OF SELECTED MATERIALS

The second-last case of the analysis aims to evaluate the effect of the recycling of selected materials from the BIPV building element on the environmental impact. For this step, selected materials of the BIPV building elements of the different products are assumed to be fully made with recycled materials. The analysis includes the recycling process of each material. Figures Figure 31-Figure 35 illustrate the benefit of the recycling processes in terms of *avoided* environmental impact. More in-depth analysis of the potential for recycling will be performed in Task 5.2-5.4 of MC2.0, the results of which will be published in upcoming WP5 deliverables.

Depending on the BIPV product, the different recycled materials considered here are aluminium, steel and glass. The PV laminate is not included in this analysis, since the building elements represent the highest weight proportion, and since not enough information are available to model the recycling of the small sized PV laminate, especially for the CIGS-based laminate. The recycling processes of the selected materials have been modelled as follows:

- The production of secondary aluminium from scraps has been modelled based on data from European Aluminium (2018)[43]
- The production of secondary steel from scraps has been assumed to be obtained with the electric arc furnace. The electric arc furnace process was available in the Ecoinvent 3.9 database ("steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria"), and has been adapted to the recycling process, by removing the virgin primary materials for steel and by reducing the electricity consumption by 72%, in according to the EuRIC Report 2020[44].
- The recycling of glass has been adapted from the IEA PVPS Report 2018[45] as avoided primary material for the production of flat glass.

An overview of the differences in impact on climate change between the BIPV product produced mainly from virgin materials (as in the Ecoinvent data representative for the current market), compared with the BIPV product considering secondary recycled materials mentioned above is presented in Figure 30. More detail of the effects of the recycling on the other impact categories is discussed in the sections below.

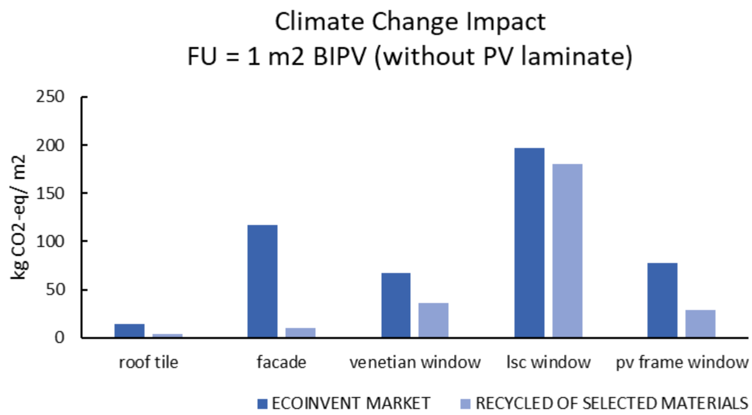


Figure 30 Climate Change impact of 1 square meter BIPV building element without PV laminate: comparison between a standard element produced considering mainly virgin materials, as from the Ecoinvent market (dark blue), and a module produced with selected recycled materials (light blue)

1. FAÇADE BIPV

For the façade BIPV, only the recycling of aluminium and steel is assumed. As a result, a very strong reduction in almost all the category is visible, reaching up to roughly 90% for the climate change category, as shown in Figure 31. This important difference between the product with recycled content and without recycled content is almost completely due to the recycling of aluminium. This is possible since the aluminium is the major cause of the climate change impact, having 93% of the total contribution of the BIPV façade building element structure – without the PV laminate - and considering that the use of recycled aluminium allows for a reduction of roughly 92% of GHG emissions compared to the use of virgin aluminium[43]. In fact, the

[43] European Aluminium. (2018). Environmental Profile Report 2018: Life-Cycle Inventory Data for Aluminium Production and Transformation Processes in Europe. Available at: https://european-aluminium.eu/wp-content/uploads/2023/01/European-Aluminium_Environmental-Profile-Report-2018_full-version.pdf

[44] EuRIC. (2020). Metal Recycling Factsheet. European Circular Economy Stakeholder Platform. Available at: https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf

[45] Stolz, P., Frischknecht, R., Wambach, K., Sinha, P., & Heath, G. (2018). Life Cycle Assessment of Current Photovoltaic Module Recycling. IEA PVPS Task 12, Report T12-13:2018. Available at: https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf

production of secondary aluminium only involves the remelting of the scraps, avoiding the bauxite mining, the extraction of aluminium oxide from the bauxite, and the following electrolysis to extract the aluminium, all processes that require higher amounts of energy inputs than the simpler remelting process[46].

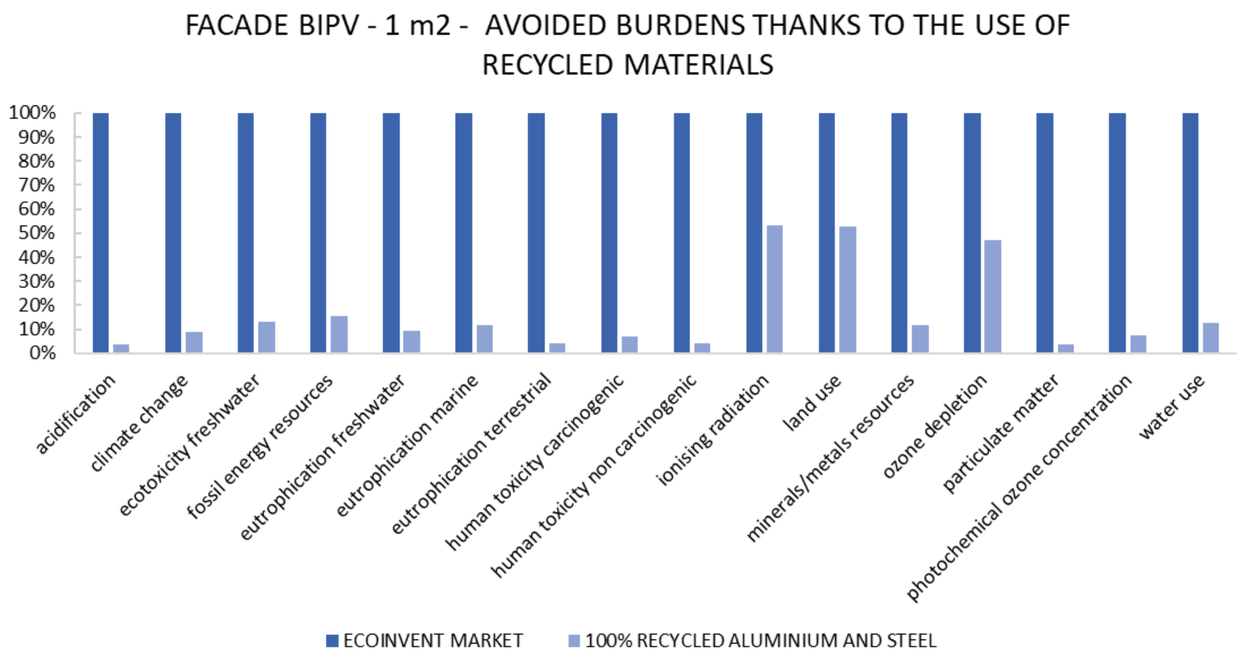


Figure 31 Difference in the EF3.1 impact categories between 1 square meter of façade BIPV building element made with virgin vs. recycled steel. (PV laminate not included)

2. ROOF TILE BIPV

For the roof tiles, since the roof tile are mainly made with steel, the recycling scenario assumes that 100% of primary steel uses comes from secondary steel. Figure 32 shows how the steel recycling is responsible for significant potential reduction in several categories, more specifically for about 70% reduction for the climate change category.

[46] European Commission, Joint Research Centre, Zore, L., Decarbonisation Options for the Aluminium Industry, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/880, JRC136525.

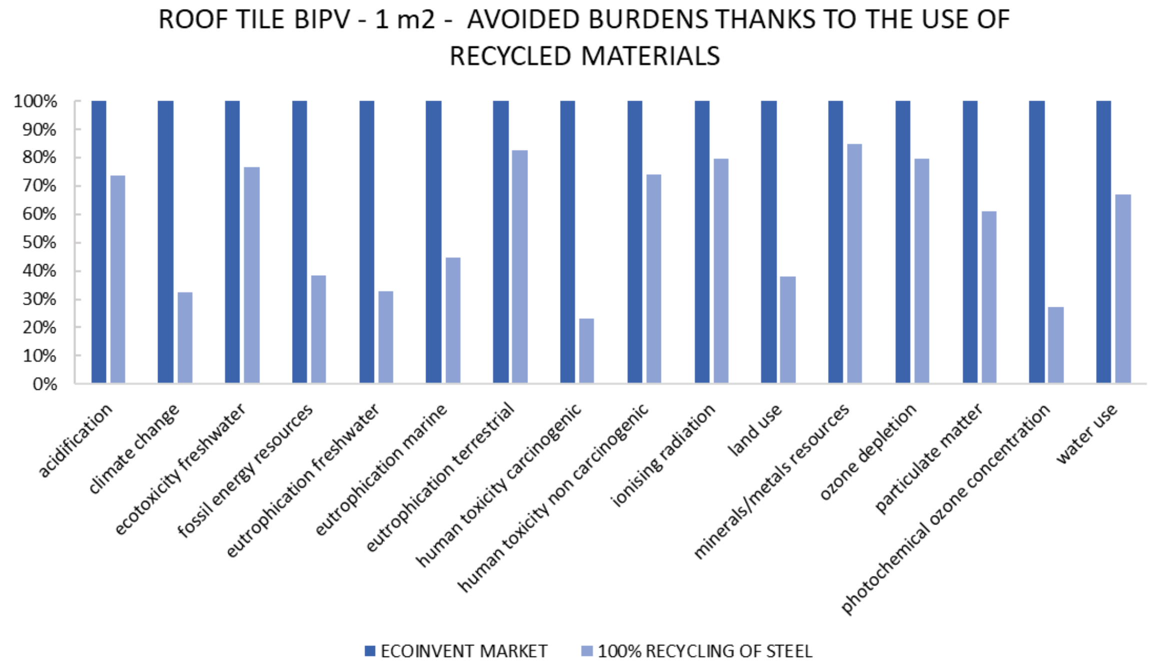


Figure 32 Difference in the EF3.1 impact categories between 1 square meter of roof tile for BIPV building element made with virgin vs. recycled steel. (PV laminate not included)

3. LSC WINDOW BIPV

For the LSC window BIPV, the recycling of aluminium, steel and glass is assumed. Despite that, the reduction in the environmental impact is not very substantial, as shown in Figure 33, since the majority of the impact is due to the PMMA slab. A recycling of PMMA slab to obtain MMA monomers is possible but not conducted at a large scale in the EU[47]. This could be highly beneficial for the impact reduction. In this model, the PMMA recycling was not assumed due to lack of LCA inventory data for this step.

[47] MMAtwo Project*: New value chain for recycling PMMA waste*. Horizon 2020. Retrieved from https://www.mmatwo.eu/

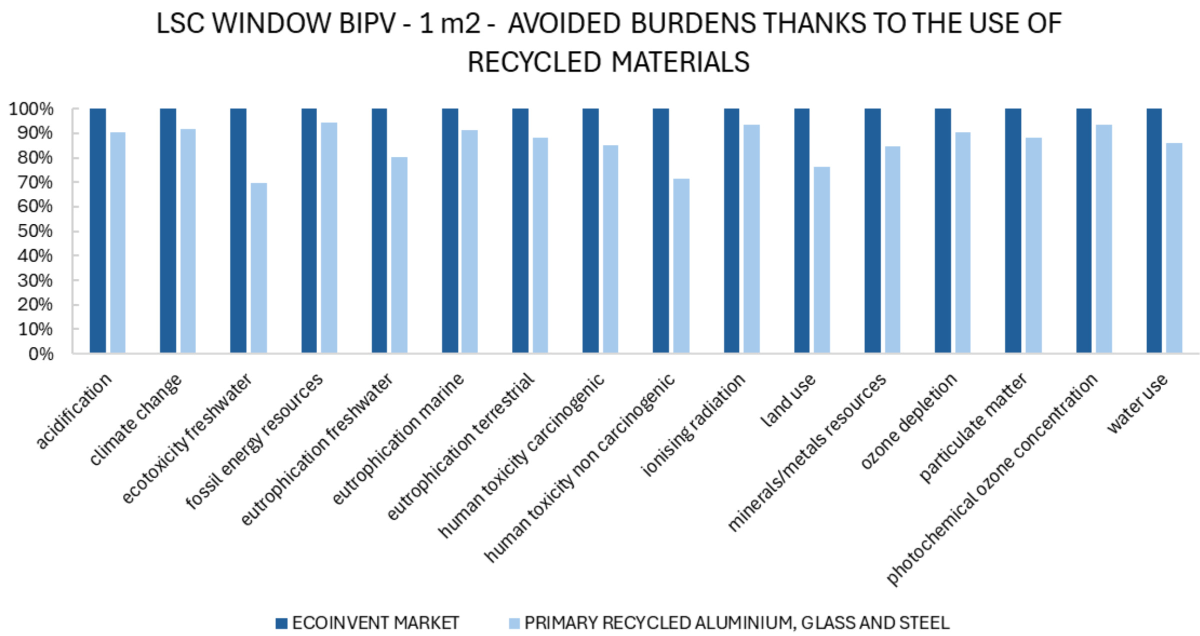


Figure 33 Difference in the EF3.1 impact categories between 1 square meter of LSC window BIPV building element, made with virgin vs. recycled glass and aluminium. (PV laminate not included)

4. VENETIAN WINDOW BIPV

For the venetian window BIPV, the recycling of steel PV blinds, aluminium and glass in the IGU have been assumed. The recycling is highly beneficial, allowing to reduce the climate change impact of about 50%, as in Figure 34.

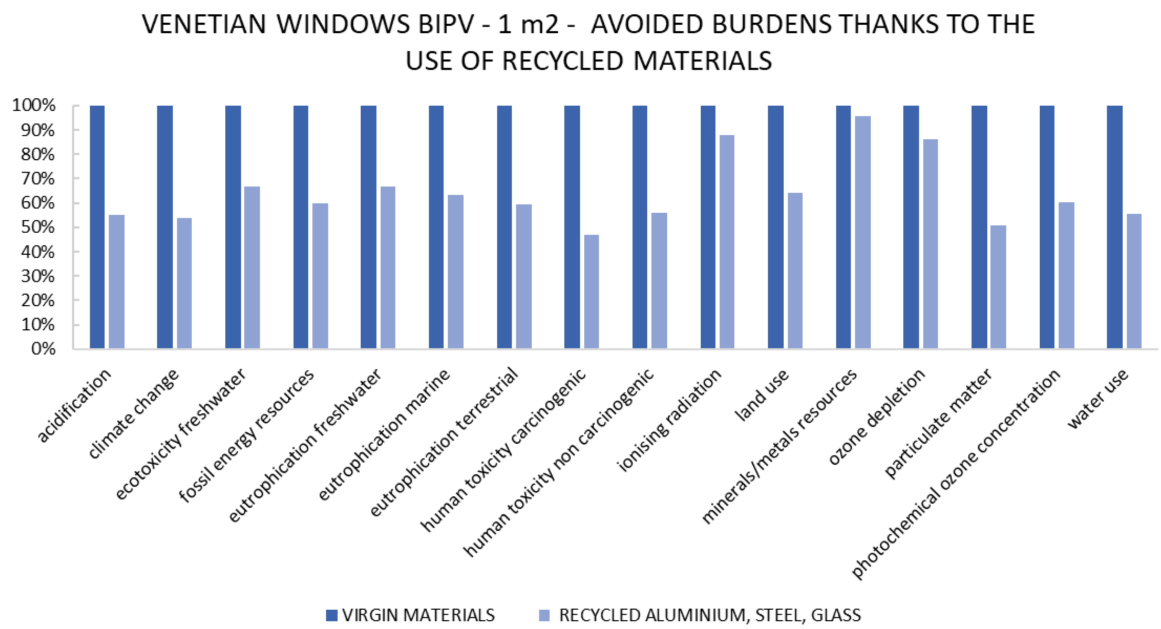


Figure 34 Difference in the EF3.1 impact categories between 1 square meter of venetian window BIPV building element, made with virgin vs. recycled glass and aluminium. (PV laminate not included)

5. WINDOW WITH PV FRAME

For the window PV frame BIPV, the recycling of glass and aluminium was assumed. This could contribute to reduce the climate change impact for about 60%, as in Figure 35.

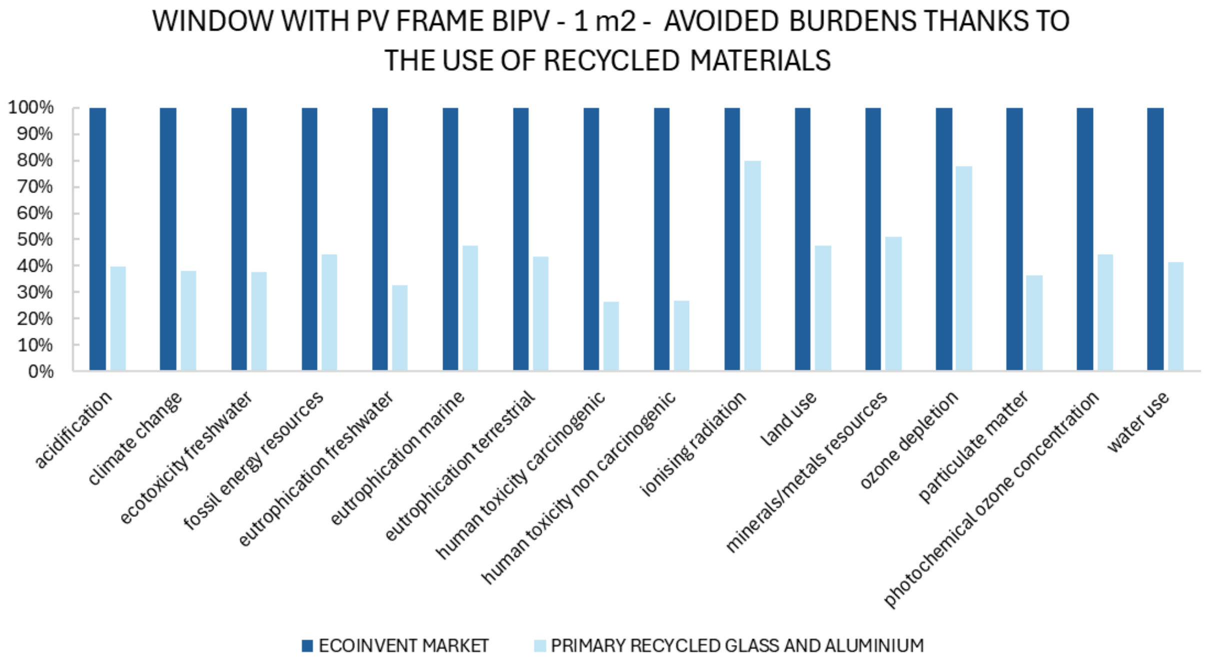


Figure 35 Difference in the EF3.1 impact categories between 1 square meter of window with PV frame building element, made with virgin vs. recycled glass and aluminium. (PV laminate not included)

4.1.5 CASE 5: PROSPECTIVE ENVIRONMENTAL ROADMAP

The objective of final and fifth case, is to evaluate a prospective roadmap for the environmental impact. This step is relevant since the BIPV current market share is still negligible, but the BIPV products are expected to hit the market in the near future. To evaluate the future impact of the BIPV products, their production was modelled assuming two different background context scenarios for decarbonization, up to 2030 and 2050, that will be here called for simplicity "worst case" and "best case". A comprehensive description of the scenarios is available in Section 3. For this step, only the square meter of building element is assumed as functional unit, since it is the major focus of this study. Only the climate change impact is evaluated, since the processes and energy generation paths are based on decarbonisation target, while the future changes for other impact categories are not considered in the future scenarios. The future impact was evaluated for the year 2020, 2030, 2050, and a linear interpolation is assumed in between. Figure 37 shows the obtained results for the different BIPV products. Focusing on the façade BIPV product as an example, in the worst scenarios it is possible to measure a total expected impact reduction of about 10% by 2050 for the CIGS PV laminate-based product, and about 54% in the best-case scenario. While for the c-Si PV the total impact expected reduction by 2050 is steeper, being about 30% and 66%, respectively for the worst- and best-case scenario, since the production of the c-Si PV laminate is highly energy intensive.

As visible in the different products shown in Figure 37 to

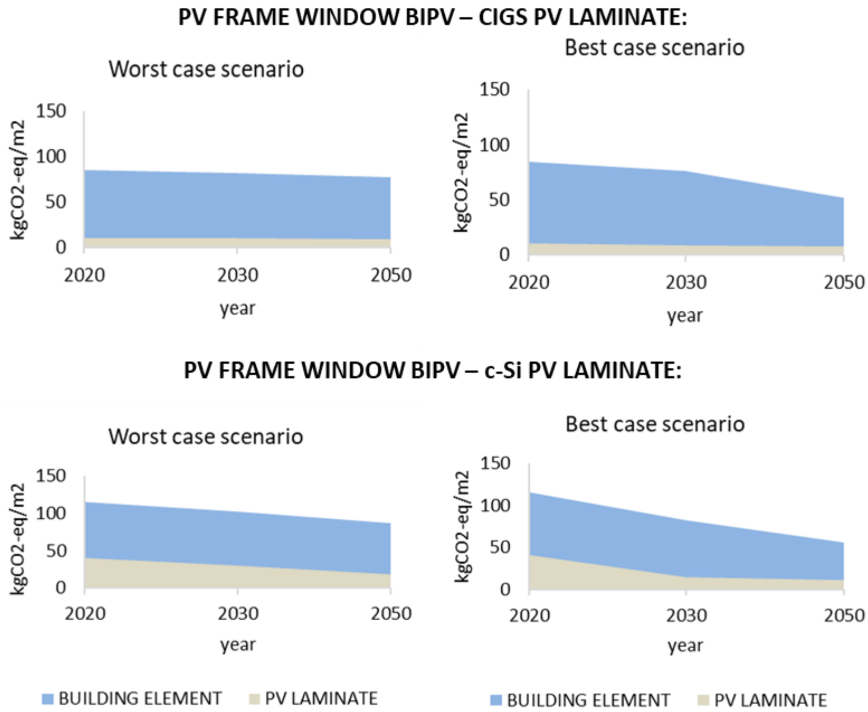


Figure 40, the results can differ consistently between the different products, due to decarbonization pathway foreseen for each of the raw material used in the BIPV products.

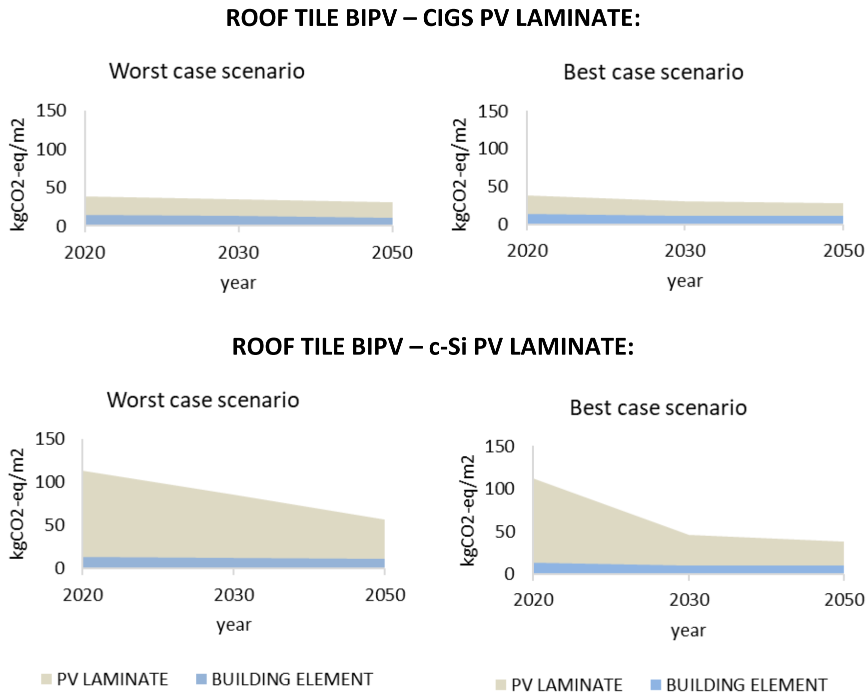


Figure 36 Prospective environmental results for 1 square meter of BIPV roof tile product, in the baseline and optimistic scenarios.

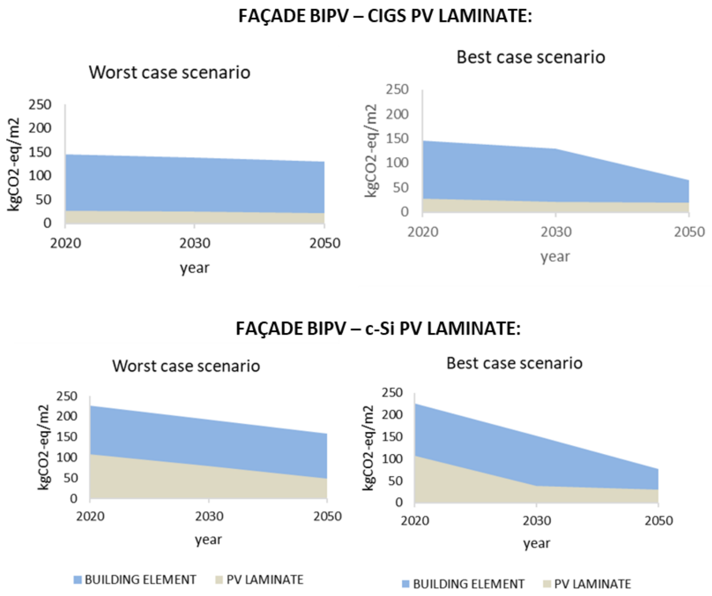


Figure 37 Prospective environmental results for 1 square meter of BIPV façade product, in the baseline and optimistic scenarios.

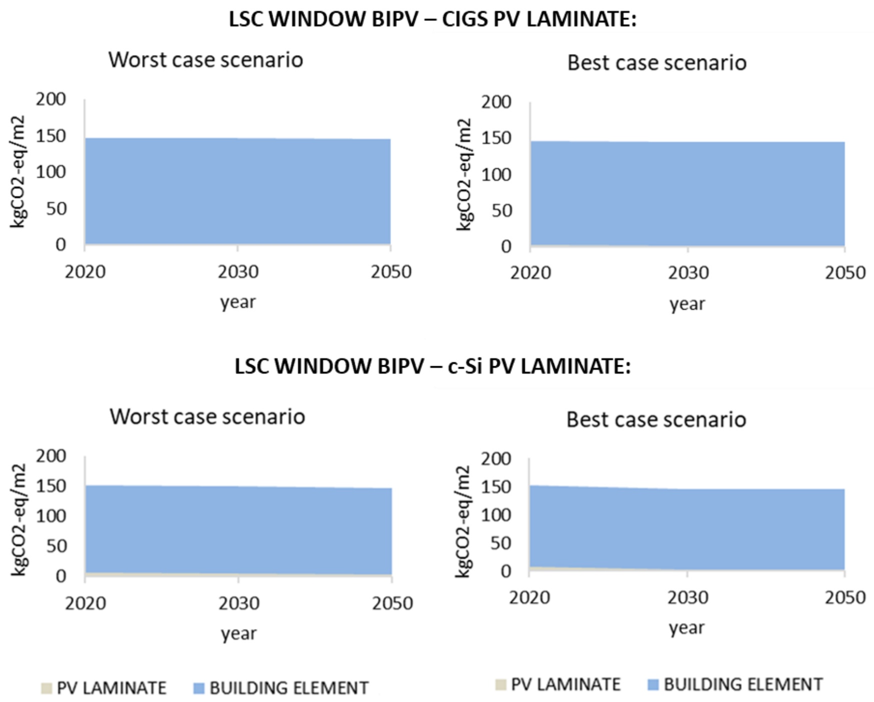


Figure 38 Prospective environmental results for 1 square meter of BIPV LSC window product, in the baseline and optimistic scenarios.

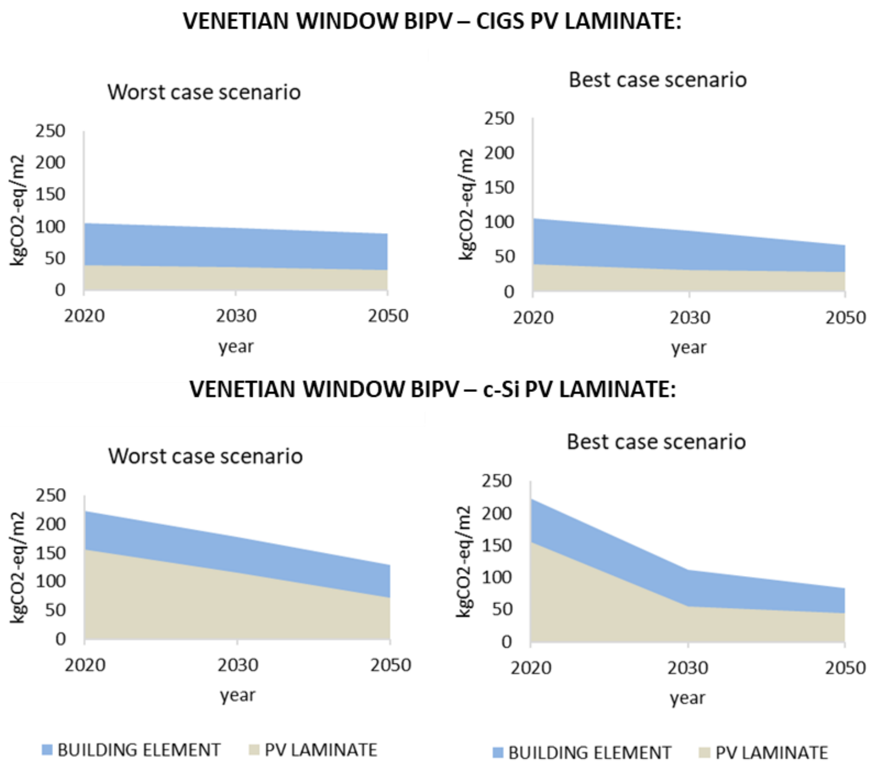


Figure 39 Prospective environmental results for 1 square meter of BIPV venetian window product, in the baseline and optimistic scenarios.

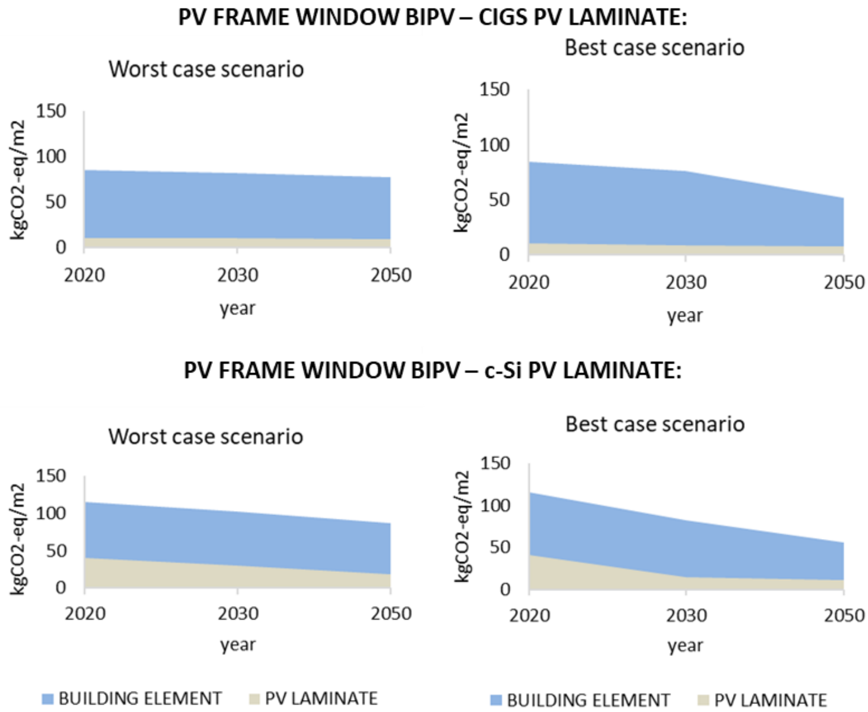


Figure 40 Prospective environmental results for 1 square meter of BIPV PV frame window product, in the baseline and optimistic scenarios.

5 Supply chain optimization

The last part of the activity is dedicated to the optimization of the supply chain, based on the results obtained from the LCA. In the LCA discussed in the previous chapters, the materials were modelled following the global market activities available in the Ecoinvent 3.9 database, except for the silicon wafer that was modelled following the IEA PVPS Task 12 Inventory[37]. In this chapter, the supply chain of the main materials required for the BIPV product were evaluated to a higher level of detail. In fact, the materials sourcing was analysed and optimized, based on the GHG emissions related to transport and electricity required for the production. These two factors were chosen as they are the key drivers for variation of the environmental impact of products manufactured in different locations. By focusing on these variables, we can also limit the effort needed for this analysis, as it is necessary to separately model each component or material for each considered location and for all MC2.0 BIPV products.

The scope of this step is in fact to regionalize the material supply and determine the locations where it could be convenient to source the main materials required for the BIPV products, in order to minimize the GHG emissions, considering that some countries might use a high share of renewable energy in their electricity mix, despite coming from a further geographical location.

The first step of the optimization was the identification of the materials with the highest GHG contribution shares, by using the LCA results. Then, the required amounts for each BIPV product were measured, based on the primary inventory data provided by the MC2.0 consortium partners. This step ensures that the most impactful materials were prioritized in the analysis. In Figures Figure 41Figure 47, the material contribution to the GHG emissions for each of the BIPV products is visualized, taking as a reference unit 1 square meter of building element, or 1 square meter of PV laminate.

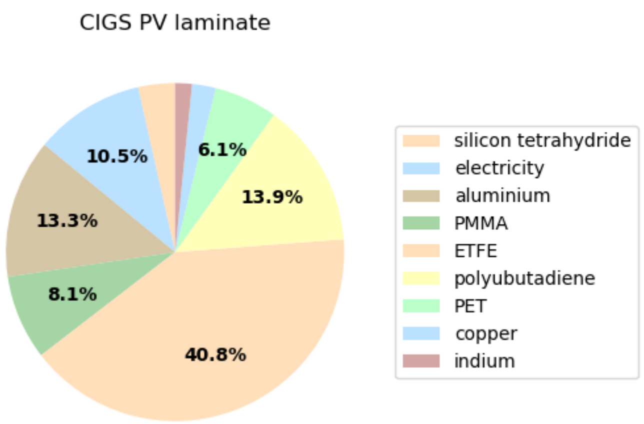


Figure 41 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of CIGS PV laminate.

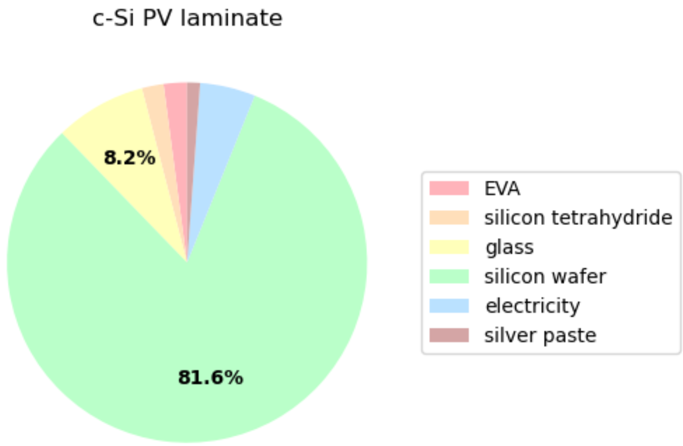


Figure 42 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of c-Si PV laminate.

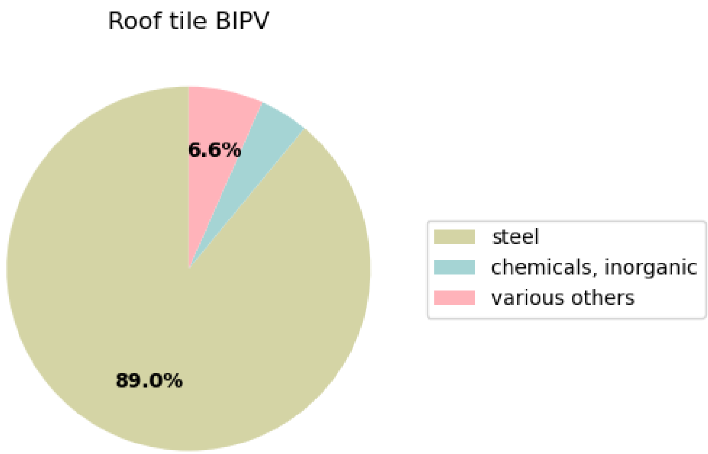


Figure 43 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of the rooftile BIPV building element.

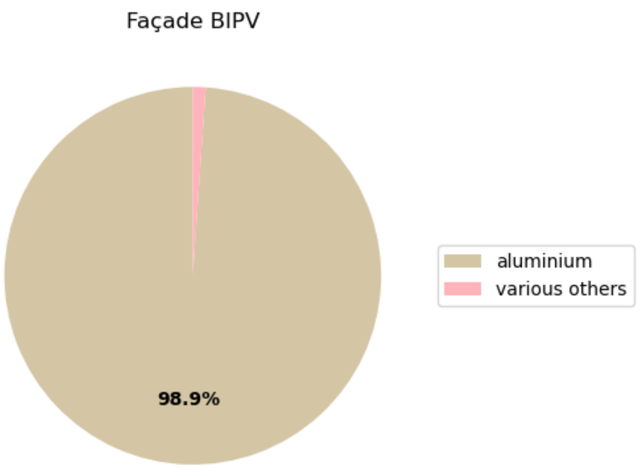


Figure 44 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of the Façade BIPV building element.

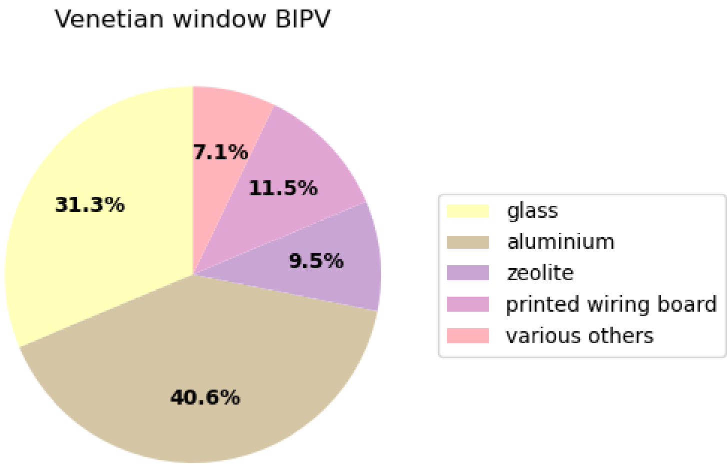


Figure 45 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of the Venetian window BIPV building element.

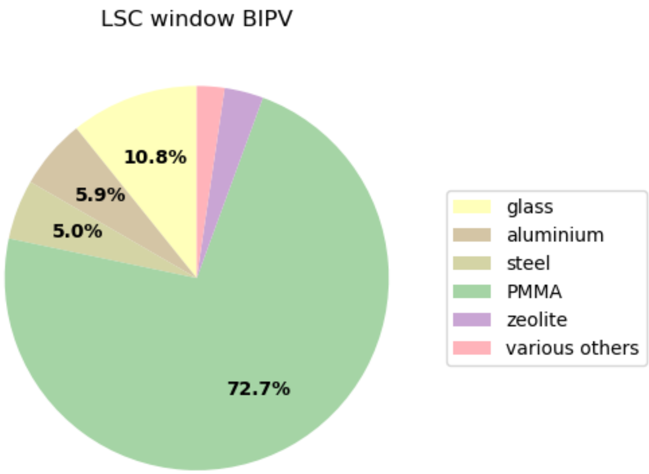


Figure 46 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of the LCS window BIPV building element.

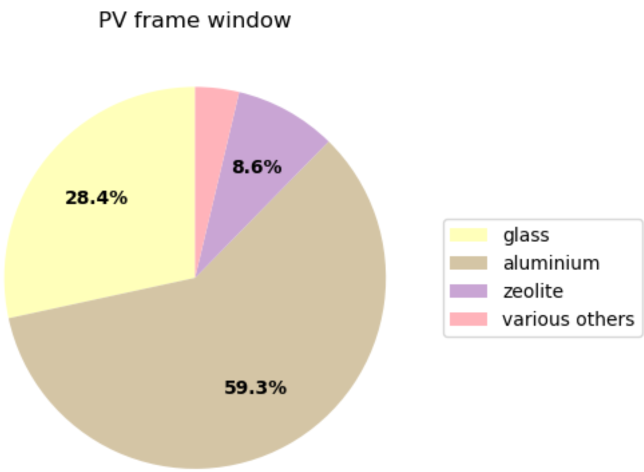


Figure 47 Contribution share to the cradle-to-gate lifecycle GHG emissions, for 1 square meter of PV frame window BIPV building element.

Next, the main locations where each of these required materials can be sourced worldwide were identified, based on available sources. For this analysis, the major producer countries of the processed materials were selected, rather than the countries where the raw primary materials are extracted. This is because we consider this analysis from the point of view of the BIPV product developers, who have essentially only direct influence on the sourcing of the input materials and components, rather than on the sourcing of all upstream materials and primary resources.

The criteria to select the materials to be included in the supply chain optimization was based on the Pareto principle, meaning that only materials with the highest contribution share to GHG emissions were included, excluding the ones with a contribution below 5%, as an assumption. Although, some materials with a contribution higher than 5% were not included, due to lack of necessary information to quantify the amount of electricity required for their production, or due to lack of relevant sources to identify the major suppliers. The materials excluded for this reason are the zeolite for the window-based BIPV, the ETFE for the CIGS PV module, and the printed wiring board for the venetian window BIPV. A list of the included materials with the major producers is available in Table 8.

Table 8 List of selected materials and main production countries.

Material	Main production countries	Source
Aluminium	Sweden, Iceland, France, Spain, Slovenia, Romania, Germany, Mozambique, Russia, Greece	RMIS[48]
Steel	Russia, Ukraine, Brazil, United Kingdom, Germany, Italy, Spain	RMIS[49]
Flat glass	Germany, France, United States, Turkey, United Kingdom, Italy, Spain, Poland, China, Belgium	EU Glass Alliance[50]
Silicon wafer	China, Germany, France, Norway, United States, Japan, South Korea, Belgium, Turkey	ESIA[51], IEA[52]
PMMA	China, United States, India, Japan, Taiwan, Germany, France, Italy, Bulgaria, Russia	S&P Global[53], PMMA EU[54]

Then the greenhouse gas (GHG) emissions factors associated with transporting these materials from the producer country to the BIPV manufacturing country were measured. To quantify the transport needs, the

48 European Commission. "Aluminium." RMIS - Raw Materials Information System. Available from https://rmis.jrc.ec.europa.eu/rmp/Aluminium.

49 European Commission. "Iron & Steel." RMIS - Raw Materials Information System. Available from https://rmis.jrc.ec.europa.eu/rmp/Iron%20&%20Steel.

50 Glass Alliance Europe. (2024). Statistical Report 2023-2024. European Commission. Available from https://www.wko.at/oe/industrie/glasindustrie/statistical-report-glass-alliance-europe.pdf#page=5

51 European Solar PV Industry Alliance. (2024). ESIA Report: Ingots and Wafers. Available from https://solaralliance.eu/wp-content/uploads/2024/03/ESIA-Report-Ingots-and-Wafers.pdf

52 IEA (2022), Solar PV Global Supply Chains, IEA, Paris https://www.iea.org/reports/solar-pv-global-supply-chains, Licence: CC BY 4.0

53 S&P Global. Chemical Economics Handbooks (CEH). S&P Global Commodity Insights, https://www.spglobal.com/commodity-insights/en/products-solutions/chemicals/chemical-economics-handbooks-ceh.

54 PMMA-online EU, https://www.pmma-online.eu/our-members/

kilometres for each means of transport were evaluated considering the major commercial routes between the raw materials production locations, and the manufacturing location of the BIPV product, selected to best represent the location of MC2.0 partners. Then, the lifecycle GHG emission factors for each mean of transport were taken from the Ecoinvent 3.9, as reported per kilogram kilometre (kg*km) in Table 9.

Table 9 Lifecycle GHG emissions factors per commercial mean of transportation

Mean of transportation	Lifecycle GHG emission [kg CO2-eq/ kg*km]	Source from the Ecoinvent 3.9 database
Sea	$1.02 \cdot 10^{-5}$	transport, freight, sea, container ship | market for transport, freight, sea, container ship | GLO
Air	$8.31 \cdot 10^{-4}$	transport, freight, aircraft, unspecified | market for transport, freight, aircraft, unspecified | GLO
Rail	$5.17 \cdot 10^{-5}$	transport, freight train | market group for transport, freight train | GLO
Road	$1.49 \cdot 10^{-4}$	transport, freight, lorry, unspecified | market group for transport, freight, lorry, unspecified | GLO

To measure the GHG emissions from electricity used in the production of each material, the electricity demand required was measured using data from available sources.

This analysis includes the electricity required to produce and shape the primary materials, excluding the raw material extraction stages. The same assumption was used to select the major manufacturing countries, excluding the countries where the raw materials are extracted, but considering the ones where the primary materials are processed. The manufacturing steps that were included for each material are represented in Figure 48 - Figure 52.

STEEL[35]

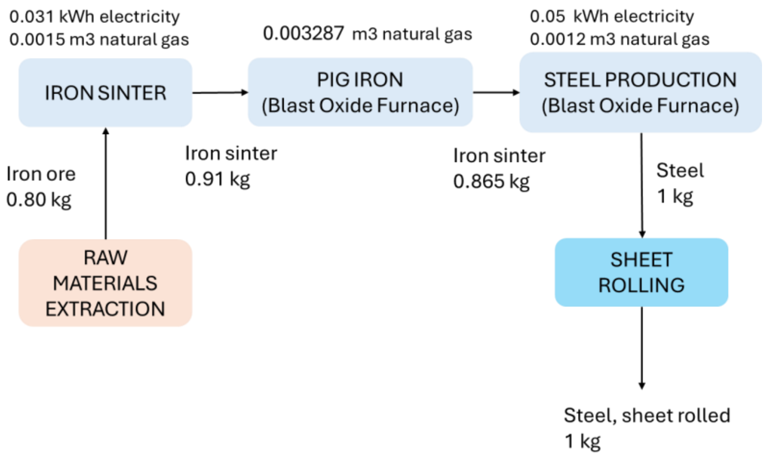


Figure 48 Schematic flow of the production, energy and mass balances for the manufacturing of steel[35].

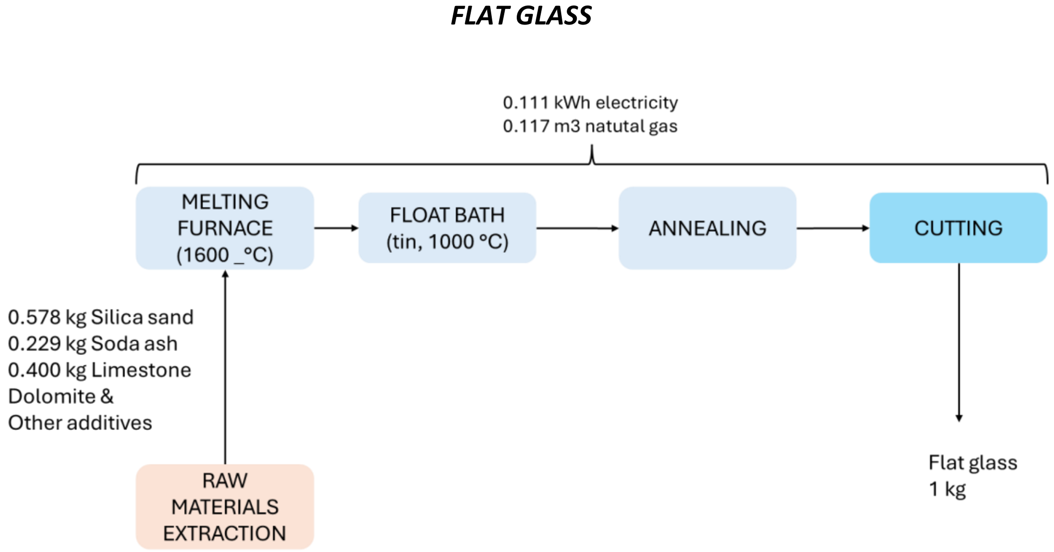


Figure 49 Schematic flow of the production, energy and mass balances for the manufacturing of flat glass[35].

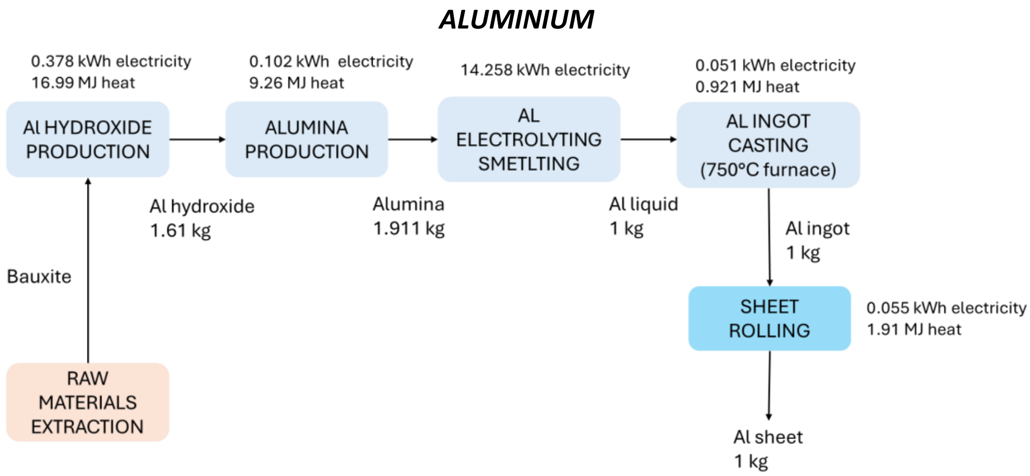


Figure 50 Schematic flow of the production, energy and mass balances for the manufacturing of aluminium[35].

SILICON

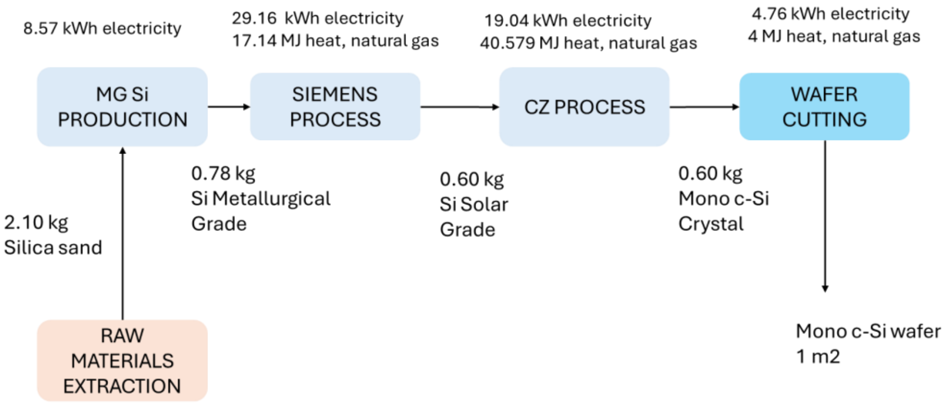


Figure 51 Schematic flow of the production, energy and mass balances for the manufacturing of silicon[37].

PMMA

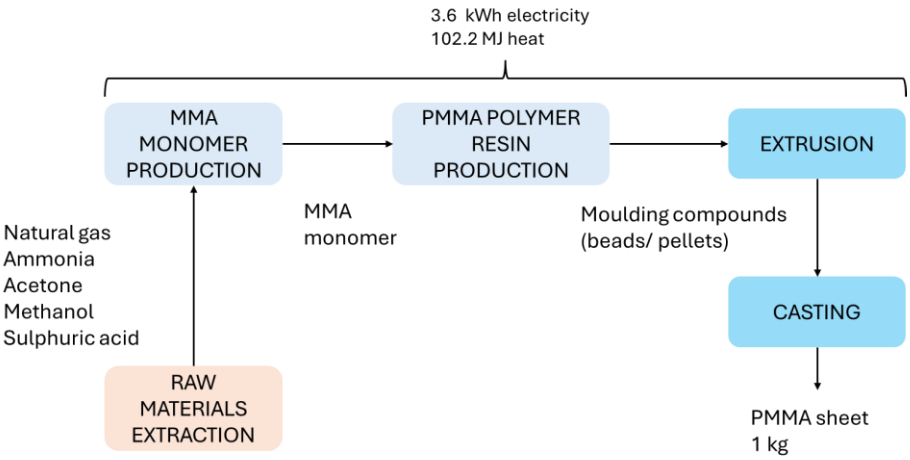


Figure 52 Schematic flow of the production, energy and mass balances for the manufacturing of PMMA[55].

Furthermore, the regionalized lifecycle GHG emission factors of the electricity mix were assigned for each of the supplier country considered. A table of the electricity GHG emission factors used is available in Table 10. It can be noted how for some countries like France, the GHG emission factor is comparable to countries with an extremely high renewable rate, such as Norway, and this is due to the high presence of nuclear power plants. On the other hand, for countries like Mozambique and Brazil, the GHG emission factor is relatively high despite a high share of renewable, because of the great amount of biomass electricity.

To facilitate decision-making, a Python-based optimization tool was developed. The tool enables the user to select as input the type of BIPV product and provides, as output, a map highlighting the main materials, their global major suppliers, and the GHG emissions related to the electricity necessary to produce the amount of material required for 1 square meter of BIPV product. Figure 53 illustrates an example of the maps obtained

[55] https://www.inference.org.uk/sustainable/LCA/elcd/external_docs/pmma_31116f01-fabd-11da-974d-0800200c9a66.pdf

as output from the optimization tool, for the LSC window BIPV product, but a similar visualization is available for the other products in ANNEX I.

As a second step, the tool also plots the total GHG emissions from transport and electricity, from each manufacturing location, depending on the BIPV product selected. This functionality allows the user to identify the most environmentally friendly supplier options. Figure 54-Figure 57 show the results for the different materials used in the LSC window BIPV product, as an example, but the results for the other BIPV products are available in ANNEX I.

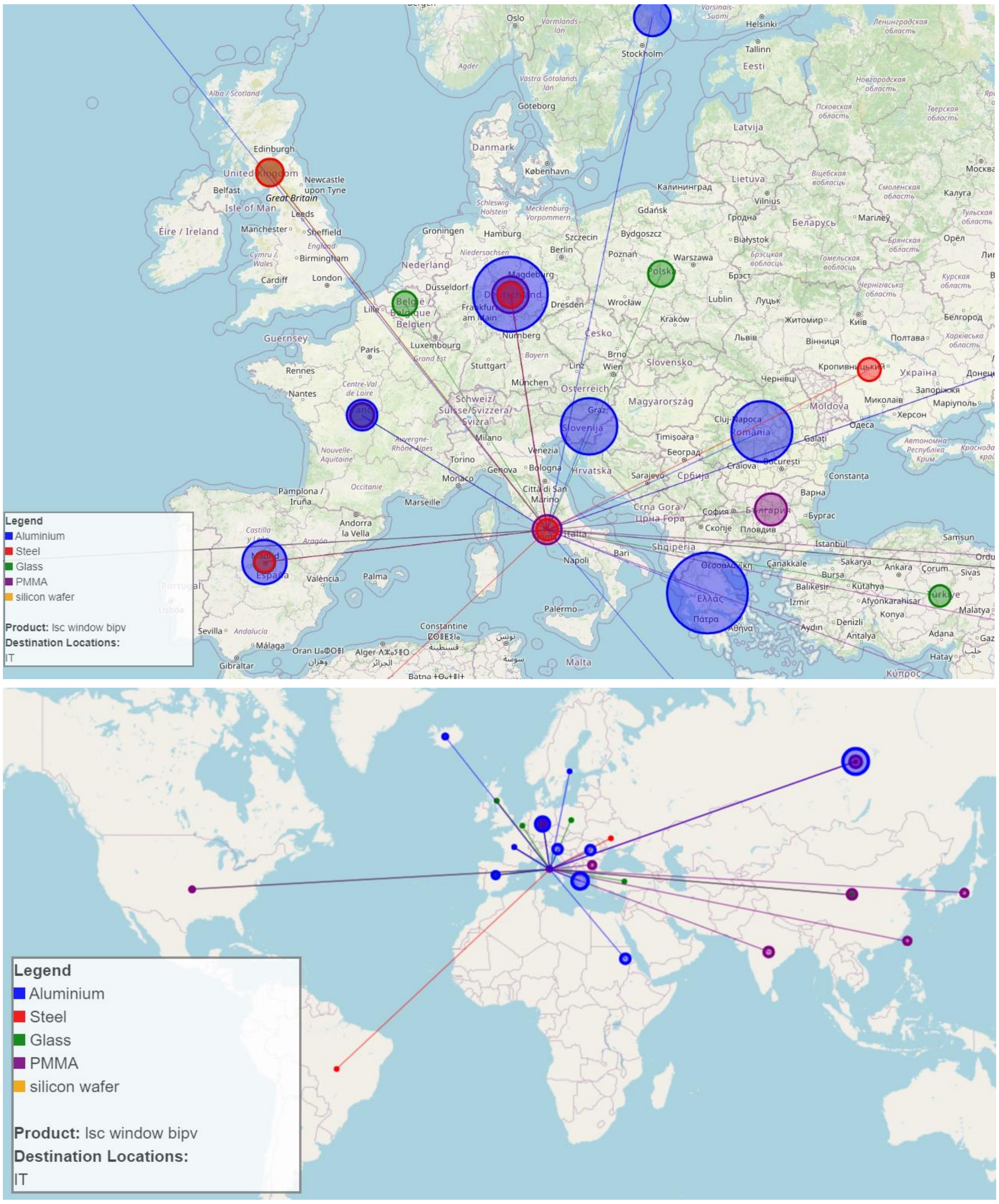


Figure 53 Example of visualization of the electricity GHG emissions of the main materials required to produce 1 square meter of LSC window based BIPV product, considering the major supplier countries. Each material is represented by a different colour, and the size of the circle is directly proportional to the GHG emissions related to electricity required to manufacture each material. Zoomed figure on Europe on the top, global suppliers on the bottom image.

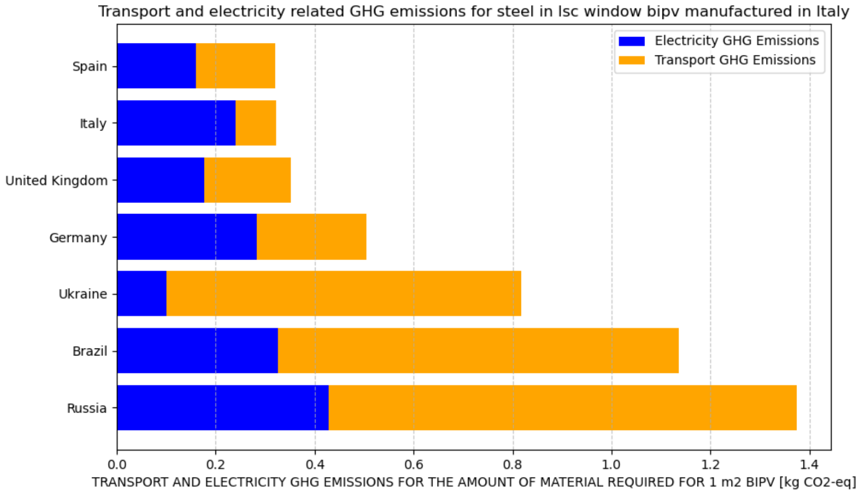


Figure 54 Transport and electricity GHG emission for the steel used in the LSC window BIPV manufactured in Italy.

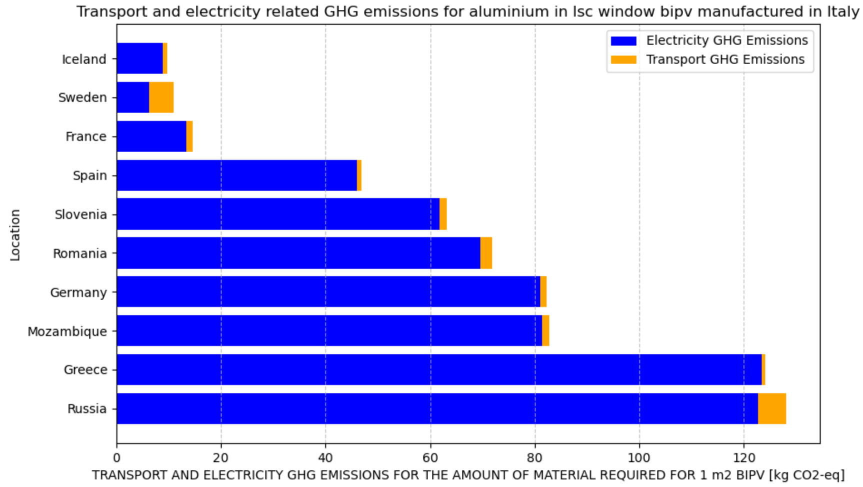


Figure 55 Transport and electricity GHG emission for the aluminium used in the LSC window BIPV manufactured in Italy.

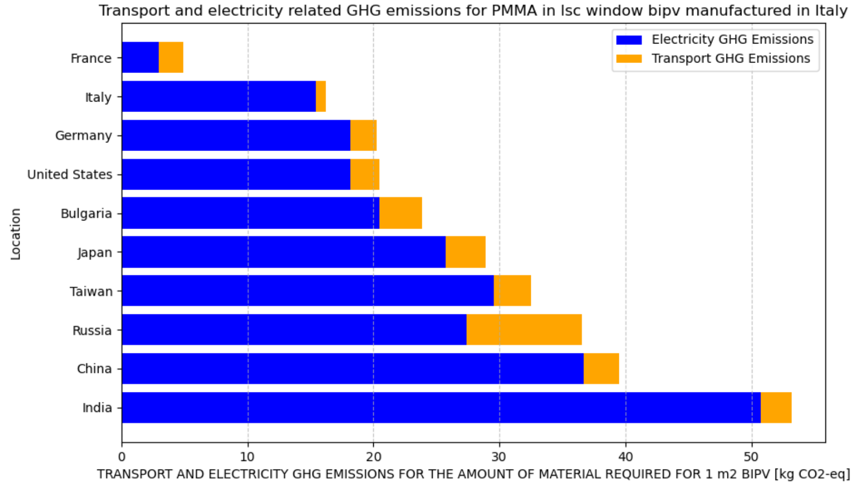


Figure 56 Transport and electricity GHG emission for the PMMA used in the LSC window BIPV manufactured in Italy.

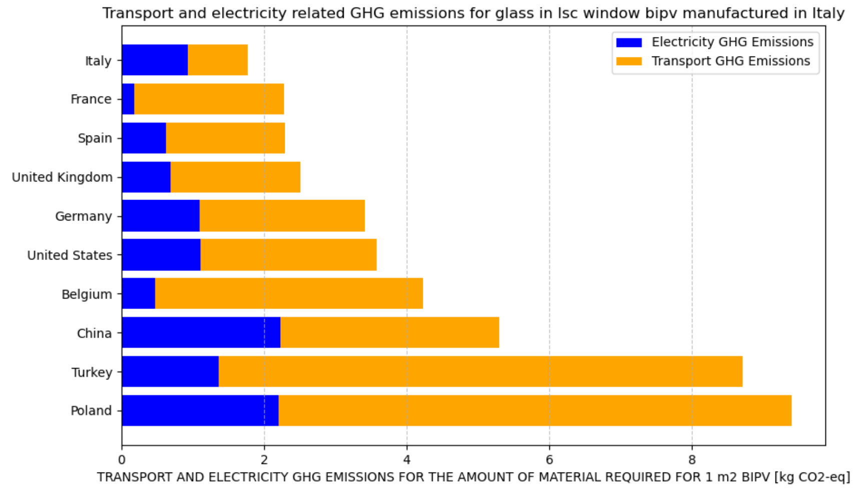


Figure 57 Transport and electricity GHG emission for the glass used in the LSC window BIPV manufactured in Italy.

Based on the results of this analysis, from the example of the LSC window BIPV application, it is possible to derive the following suggestions to optimize the supply chain of the product: the best supplier countries in terms of GHG emissions from transport and electricity for aluminium would be Iceland, Sweden or France; for the steel it would be Spain, Italy and United Kingdom; for the PMMA France; for the glass Italy, France, Spain or United Kingdom.

As intuitive, the more the material is heavy and highly required in the BIPV product, the more the transport emissions are relevant. This is the case for glass or steel in the LSC window BIPV example. On the contrary, the more a material is light and/or electricity-intensive, the higher is the contribution of the grid electricity GHG emissions. This is the case for PMMA and aluminium in the LSC window BIPV product.

Similar conclusions can be drafted for the other BIPV products. The tool can be personalized with other types of products as an input, and the analysis can be extended considering different parameters to be optimized, such as the manufacturing cost.

In this study, only the GHG emissions coming from electricity are included. For a more comprehensive analysis, also the amount of heat would be included in the optimization. Although, to achieve that, a case-by-case industry analysis would be needed, since the GHG emissions from heat production are very difficult to regionalize by country. In fact, they depend on the specific needs of each industrial sector, or on the policy of each factory, rather than on the manufacturing country.

6 Conclusions

To summarize all the analysis, the goal of this report was to identify environmental hotspots for the BIPV products developed within the MC2.0 project, to provide an environmental roadmap for the impact of these products expected in the future years, and suggest an optimized supply chain based on environmental criteria.

In literature available studies, there is still a lack of harmonization and guidelines specific for BIPV LCA assessments, which makes the results harder to compare. Results available in the public EPDs are instead easier to compare, but they are mainly related to building elements without PV.

From the first case dedicated to the PV laminate assessment, it can be concluded that the c-Si based has an overall higher impact than the CIGS one For both laminate types, it is crucial to replace the ETFE, which contributes majorly to ozone depletion. In this assessment, ETFE has been selected as a standard for CIGS laminates, while the glass backsheet has been selected as a standard for c-Si laminates. In a sensitivity analysis, the CIGS and c-Si PV laminates were modelled with both glass and ETFE frontsheets.

The use of glass instead of ETFE improves massively the impact on the ozone depletion category, but only slightly in the other categories. When different frontsheets are selected for either CIGS or c-Si, the difference in results might increase significantly.

Furthermore, the sourcing of the c-Si wafer from manufacturers which makes use of renewable energy could improve substantially the sustainability of the c-Si PV laminate. For both laminate types, if the frontsheet is made with ETFE material, this has a relevant contribution to the ozone depletion categories. Despite that, the ozone depletion category is not highlighted as the most important one, that being instead the minerals and metals resources depletion, followed by climate change impact categories.

From the analysis of the BIPV products, the environmental hotspots are different, depending on the BIPV type, and depending on the area coverage of the PV laminate. As an example, for façade products the aluminium has on overall the highest contribution, the impact of roof tiles is lower compared to the other products, while the impact of the LSC windows is the highest, due to the PMMA slab production.

Enlarging the analysis on the entire BIPV system, by adding the BOS, it is visible how the impact on mineral and metal resources increases consistently, due to the inverter in the BOS.

Other relevant impact categories for the entire BIPV system are the climate change, and freshwater one.

Since the efficiency is not yet defined for the BIPV products under analysis, the results have been evaluated considering the efficiency as a parameter, considering the benchmark value of the PERC roof mounted PV as maximum upper limit, and a reduction of 50% respect the best estimated value as lower limit. The resulted GHG emissions were evaluated per kWp of installed capacity and per kWh of electricity generated.

In both cases, we could observe how the GHG emissions are strongly affected by the electrical efficiency, and if the efficiency is halved, the GHG emissions might arrive way above the benchmark value of the PERC roof mounted PV.

When compared to traditional building elements, BIPV have higher GHG emissions per square meter. However, GHG emissions of BIPV are lower per kWh, when the electricity produced with BIPV is compared with a non-renewable-based grid electricity production. This is true for all the products analysed, with the best estimated efficiency, both paced in a best south orientation and in a north worst oriented surface.

In order to understand what the future impact of the BIPV products, a prospective LCA has been performed, modelling the products in two background market scenarios – a best and a worst case - for the years 2020, 2030 and 2050. As a result on the climate change impact, it is possible to observe how results can differ consistently between the different products, due to decarbonization pathway foreseen for each of the raw material used in the BIPV products. As an example, for the CIGS PV laminate-based façade product, it is possible to measure a total expected impact reduction by 2050 of about 10% in the worst-case scenario, and

54% in the best-case scenario. While for the c-Si PV the total impact expected reduction by 2050 is steeper, being about 30% and 66%, respectively for the worst- and best-case scenario, due to the fact that the production of the c-Si PV laminate is highly energy intensive.

More investigation on how the scenarios of decarbonization pathways affects each of the materials is required in future and can be investigated in future research studies.

As a last step, the LCA inventory and results were used to perform a supply chain optimization. The optimization aims to reduce the GHG emissions coming from electricity and transport, for the main materials required to manufacture each BIPV product. As a result, it is possible to conclude how for light materials and/ or materials that are required in a little amount, the transport has a relatively low contribution to the GHG emissions, compared to the electricity required to the manufacturing of the material. As intuitive, countries with a higher share of renewables or nuclear in the electricity grid production mix, have a significantly lower impact, compared with countries with a high share of fossils or renewable biomass in the grid mix.

As a limitation, this analysis only takes into account the climate change impact category. In the future, it would be relevant to couple this assessment including in the optimization other impact categories, such as resource use, human or ecosystem health, but also monetary indicators.

Furthermore, for several materials are energy intensive because of the heat consumption, rather than the electricity consumption. Emissions coming from the heat production are specific for each industrial sectors, and are more difficult to regionalize, and they were excluded from the present assessment, but might be included in future activities for a complete analysis.

ANNEX I – Results of the supply optimization

Table 10 List of the sources locations included and relative lifecycle GHG emissions factors, as from the "market for electricity, medium voltage" processes available in the Ecoinvent 3.9 database.

SOURCE LOCATION	RENEWABLE SHARE[56] [%]	ELECTRICITY GHG EMISSIONS FACTORS[35] [kgCO2-eq/kWh]
Norway	97.80%	0.03
Sweden	68.30%	0.04
Iceland	100.00%	0.05
France	24.00%	0.08
Ukraine	16.50%	0.17
Belgium	25.50%	0.20
Spain	42.00%	0.27
United Kingdom	41.70%	0.29
Slovenia	29.90%	0.36
Italy	35.40%	0.40
Romania	42.20%	0.40
Germany	43.30%	0.47
United States	21.30%	0.47
Mozambique	84.10%	0.47
Bulgaria	19.10%	0.53
Brazil	87.70%	0.54
Turkey	42.00%	0.59
Japan	21.50%	0.67
South Korea	7.40%	0.70
Russia	17.90%	0.71
Greece	42.60%	0.72
Taiwan	7.60%	0.77
Poland	21.00%	0.95
China	29.70%	0.95
India	19.50%	1.32

[56] IRENA (2024), Renewable energy statistics 2024, International Renewable Energy Agency, Abu Dhabi

Figure 58 Visualization of the location of the major suppliers of the main materials required to produce 1 square meter of c-Si PV laminate. The dimension of the circle is directly proportional to the GHG emissions required from electricity to produce the amount of material required

Figure 59 Visualization of the location of the major suppliers of the main materials required to produce 1 square meter of venetian window BIPV product. The dimension of the circle is directly proportional to the GHG emissions required from electricity to produce the amount of material required

Figure 60 Visualization of the location of the major suppliers of the main materials required to produce 1 square meter of roof tile BIPV product. The dimension of the circle is directly proportional to the GHG emissions required from electricity to produce the amount of material required

Figure 61 Visualization of the location of the major suppliers of the main materials required to produce 1 square meter of LSC window BIPV product. The dimension of the circle is directly proportional to the GHG emissions required from electricity to produce the amount of material required

Figure 62 Visualization of the location of the major suppliers of the main materials required to produce 1 square meter of façade BIPV product. The dimension of the circle is directly proportional to the GHG emissions required from electricity to produce the amount of material required

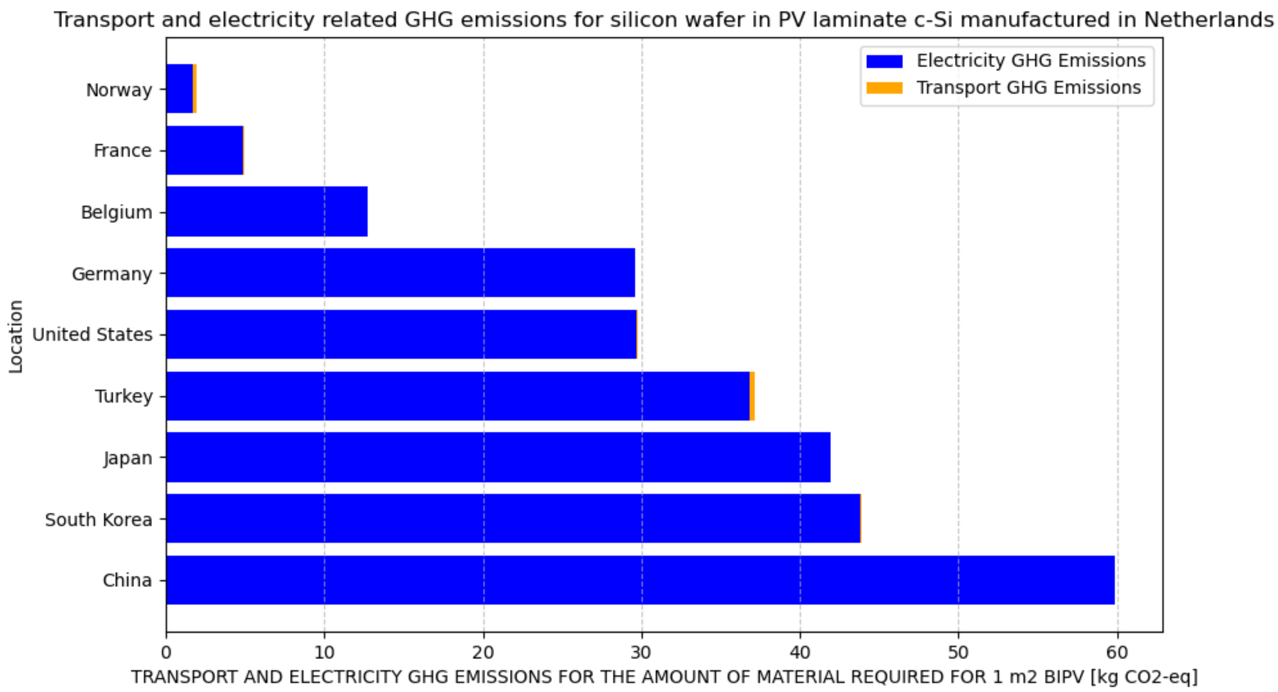


Figure 63 Transport and electricity GHG emissions for the amount of silicon wafer required to manufacture 1 square meter of c-Si PV laminate.

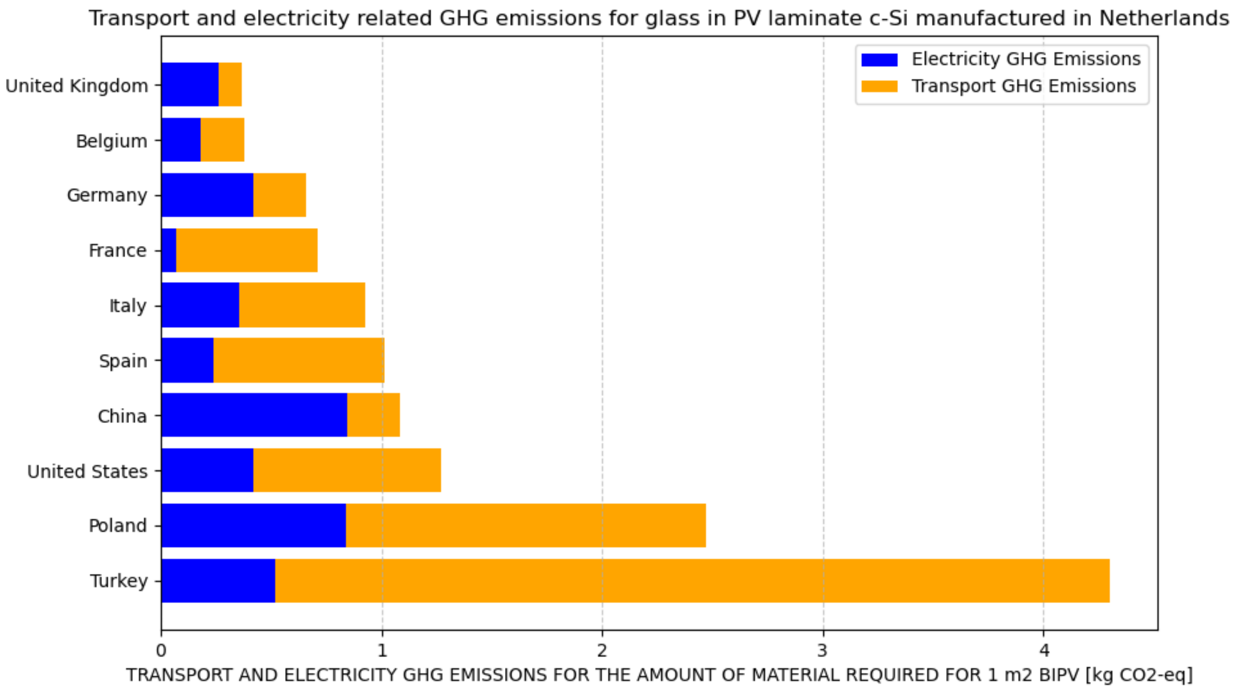


Figure 64 Transport and electricity GHG emissions for the amount of glass required to manufacture 1 square meter of c-Si PV laminate.

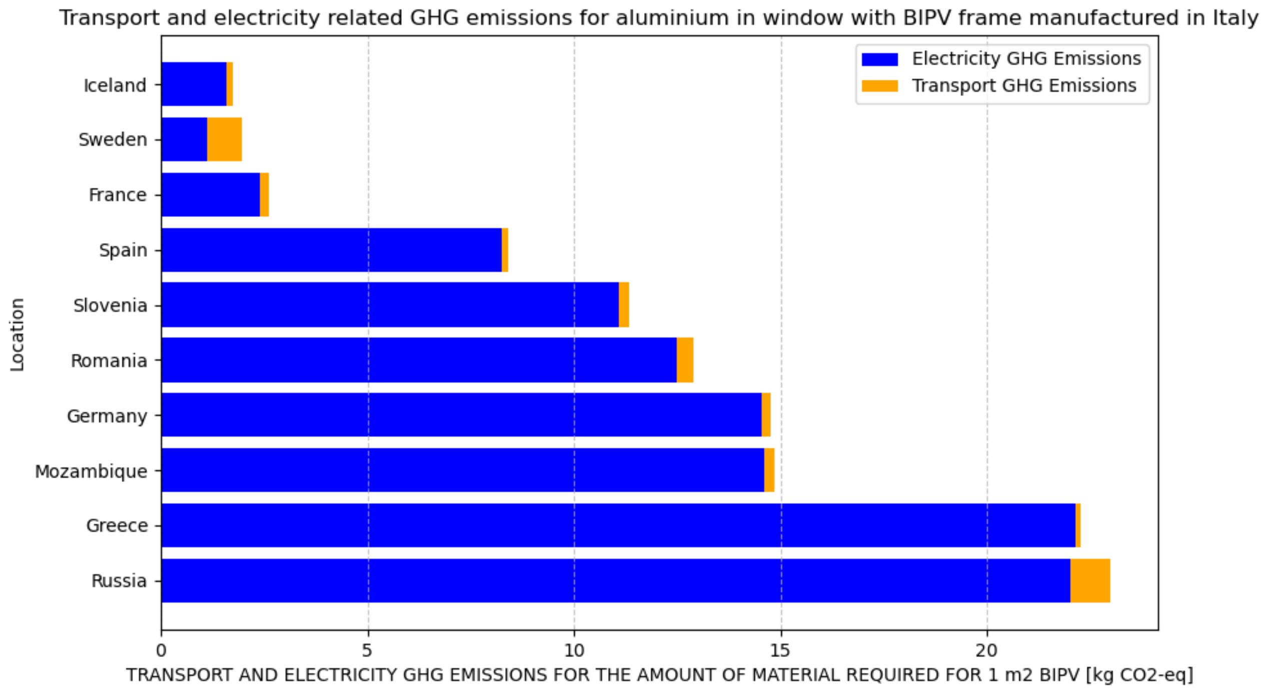


Figure 65 Transport and electricity GHG emissions for the amount of aluminium required to manufacture 1 square meter of window with BIPV frame product.

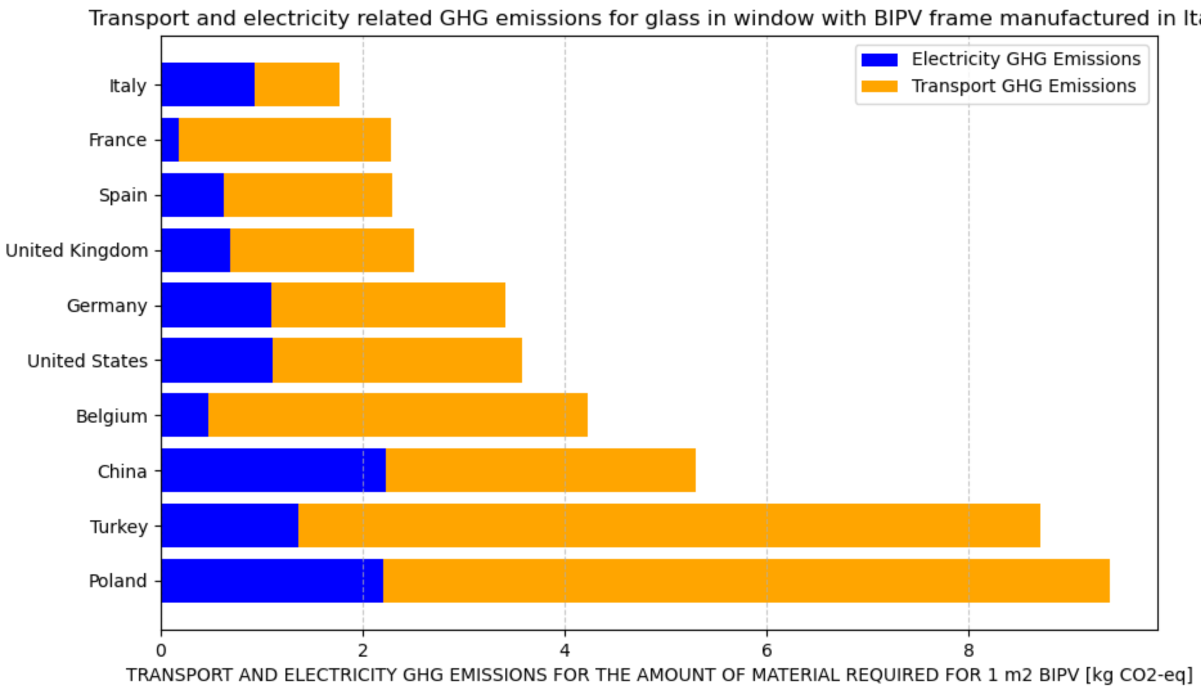


Figure 66 Transport and electricity GHG emissions for the amount of glass required to manufacture 1 square meter of window with BIPV frame product.

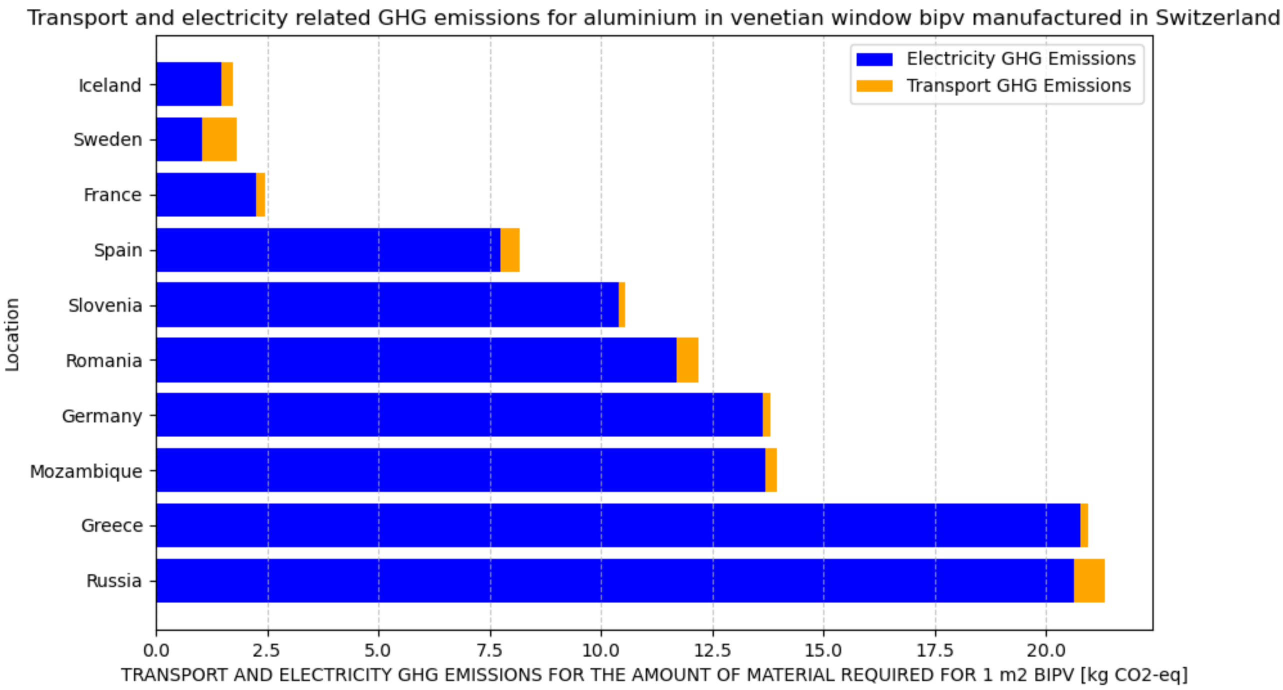


Figure 67 Transport and electricity GHG emissions for the amount of aluminium required to manufacture 1 square meter of venetian window BIPV product.

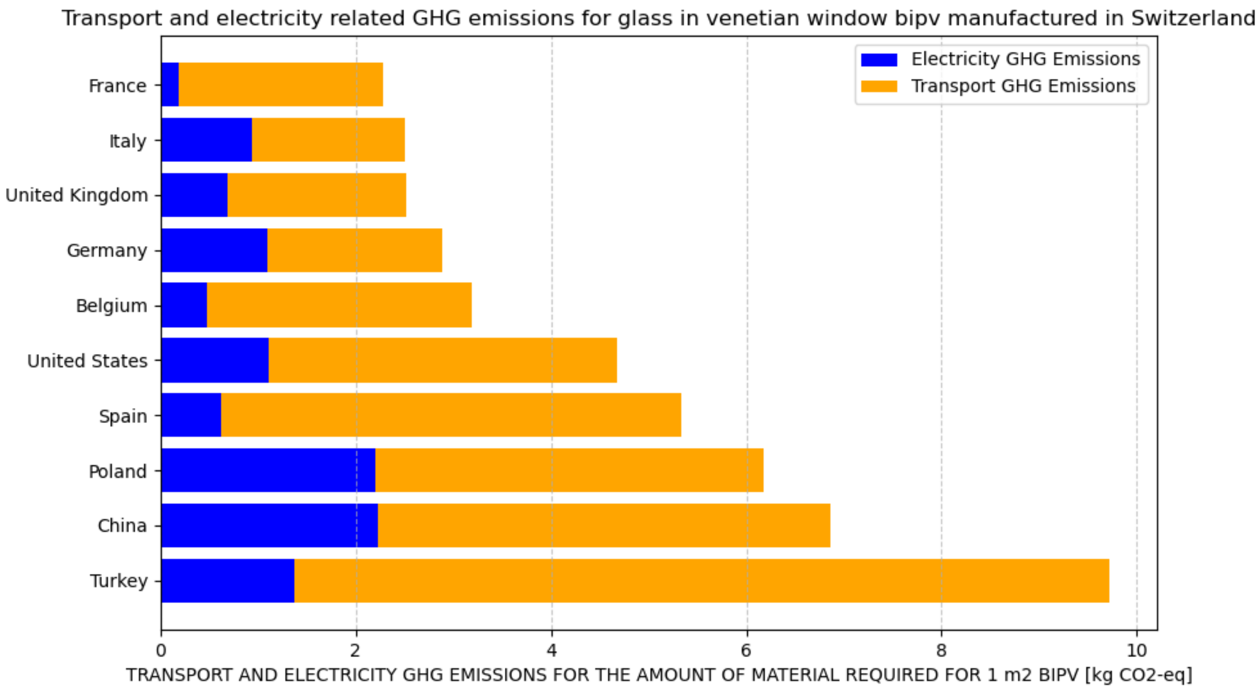


Figure 68 Transport and electricity GHG emissions for the amount of glass required to manufacture 1 square meter of venetian window BIPV product.

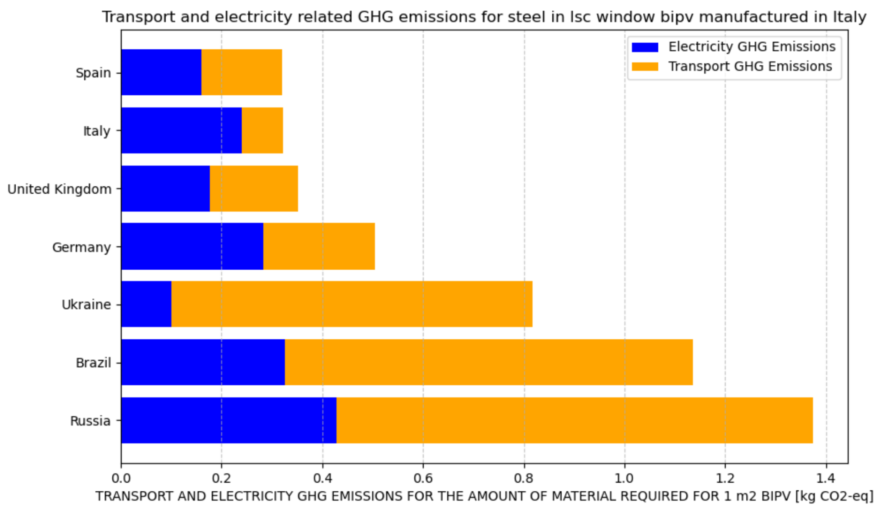


Figure 69 Transport and electricity GHG emissions for the amount of steel required to manufacture 1 square meter of LSC window BIPV product.

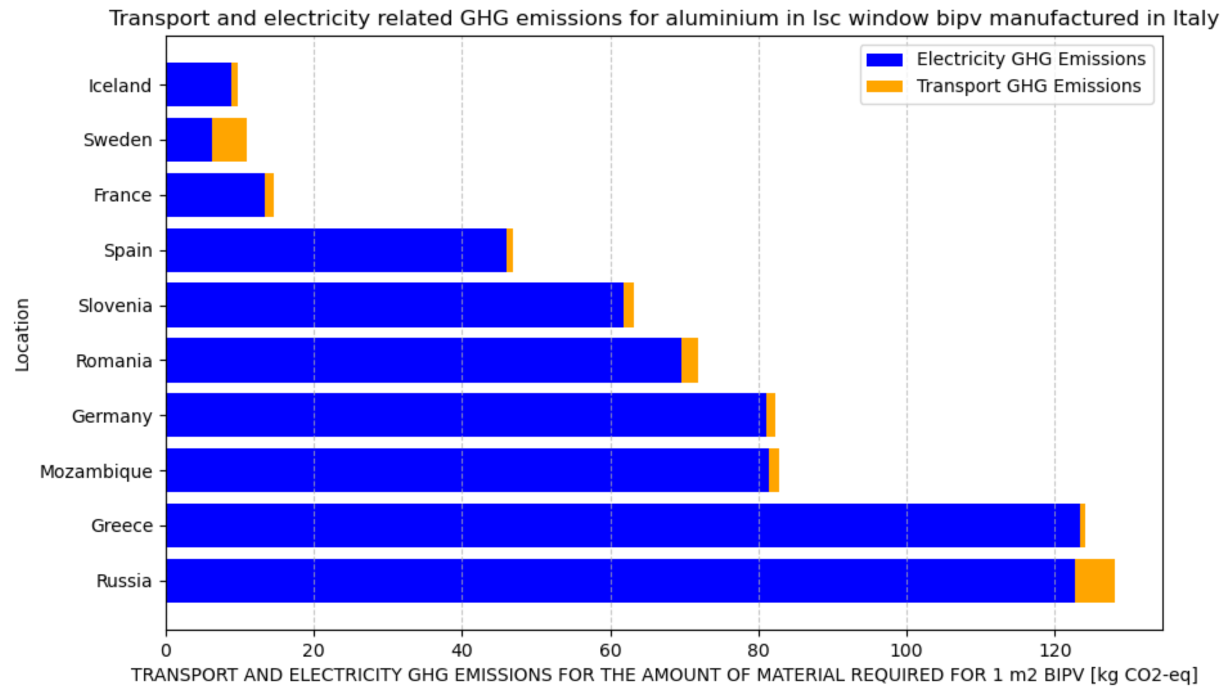


Figure 70 Transport and electricity GHG emissions for the amount of aluminium required to manufacture 1 square meter of LSC window BIPV product.

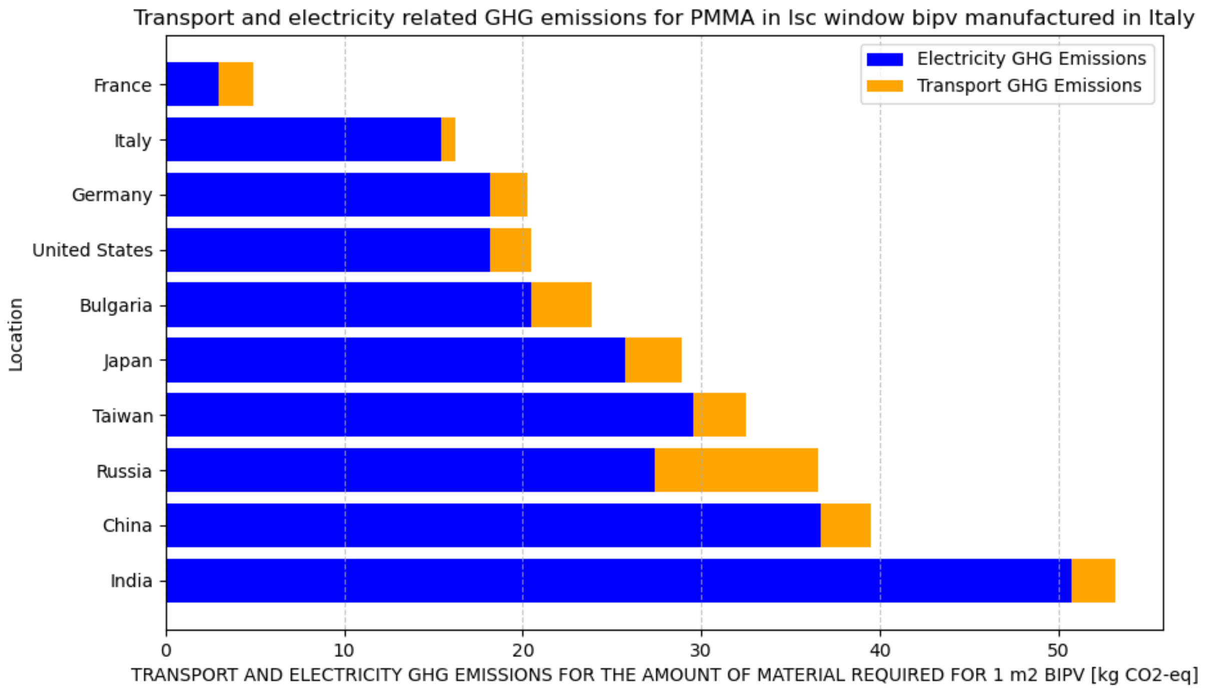


Figure 71 Transport and electricity GHG emissions for the amount of PMMA required to manufacture 1 square meter of LSC window BIPV product.

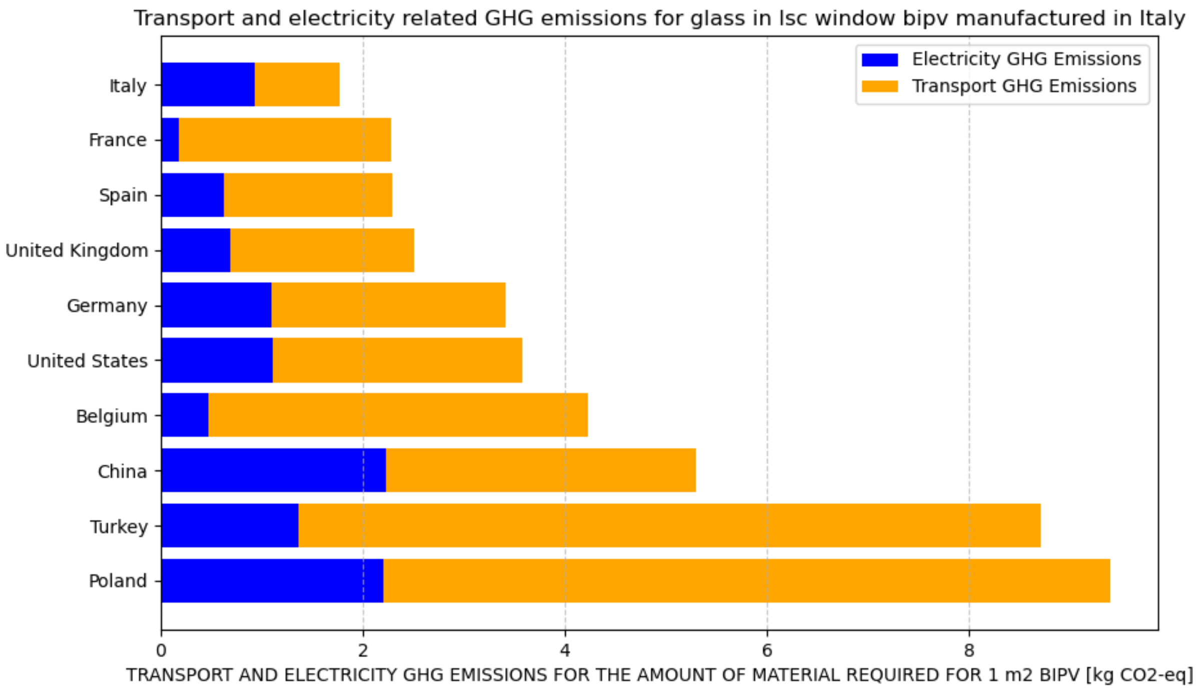


Figure 72 Transport and electricity GHG emissions for the amount of glass required to manufacture 1 square meter of LSC window BIPV product.

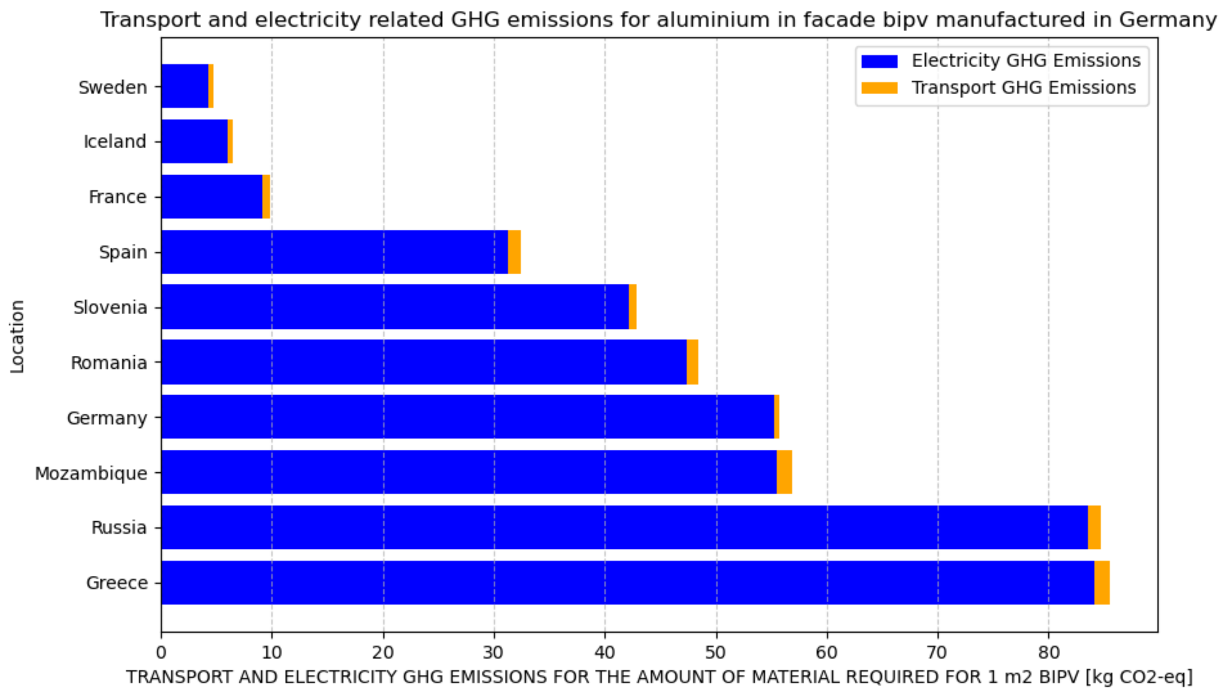


Figure 73 Transport and electricity GHG emissions for the amount of aluminium required to manufacture 1 square meter of façade BIPV product.

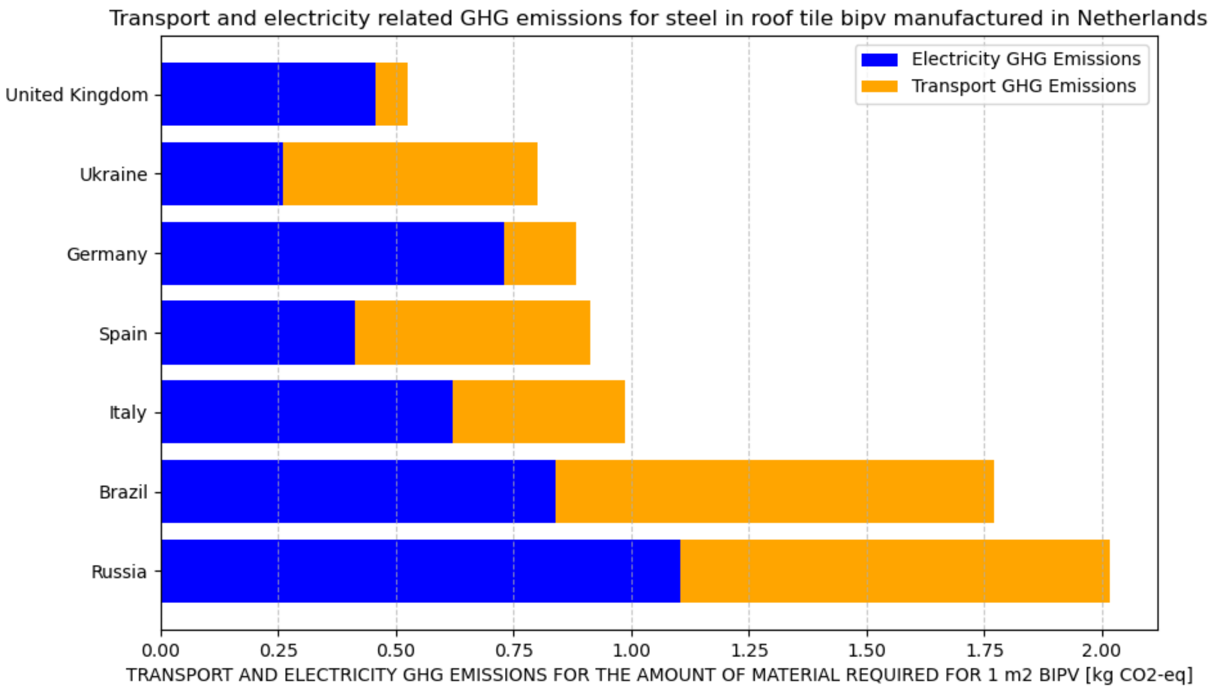


Figure 74 Transport and electricity GHG emissions for the amount of steel required to manufacture 1 square meter of roof tile BIPV product.