Ref. Ares(2025)6166653 - 29/07/2025

Environmental performance and circularity analysis of the proposed SYMBIOSYST technologies

Symbiosyst

Horizon Europe EU project
Grant Agreement No. 101096352



Funded by the European Union

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Document control sheet

Project	**SYMBIOSYST – Create a Symbiosis where PV and agriculture can have a mutually beneficial relationship**

Topic identifier	HORIZON-CL5-2022-D3-01-06
Grant Agreement N°	101096352
Coordinator	ACCADEMIA EUROPEA DI BOLZANO
Duration	01/01/2023 – 31/12/2026
Work package N°	WP4
Work package title	Sustainable agri-PV
Work package leader	UPC
Task n°	4.2
Task leader	UPC
Document title	Environmental performance and circularity analysis of the proposed SYMBIOSYST technologies
Lead Beneficiary	UPC
Dissemination level	Public
Authors	Marcel Macarulla, Giulia Torri, David Caballero, Arvid Van der Heide
Contributors	
Reviewer(s)	Arvid Van der Heide, Cristina Polacchi
Issue date	30/06/2025

History of versions

Version	Date	Author - Beneficiary	Comments
v00	01/06/2025	Marcel Macarulla - UPC	1st draft with all partners inputs
v01	26/06/2025	Marcel Macarulla - UPC	Final version after the reviewers' feedback and the partners' corrections

Acknowledgements

The work described in this publication has received funding from the European Union Horizon Europe research and innovation programme under grant agreement Nº 101096352.

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Executive Summary

This deliverable presents the outcomes of Task 4.2 of WP4 "Sustainable agri-PV", focused on the assessment of the environmental performance and circularity potential of the proposed SYMBIOSYST solutions, together with the results of those activities from Task 4.1 that were originally planned for Deliverable D4.1 "Eco-design requirements and guidelines for agri-PV" and have now been integrated into this report. The results of these activities are presented in Section 2.

The Life Cycle Assessment (LCA) studies conducted under Task 4.2 are presented in Section 3. These include the comparative assessment of innovative mounting structures (steel vs wood), developed in collaboration with Task 3.1, which has directly supported the decision-making process for Milestone MS4 "Use of wood for mounting structures". In addition, the LCA of the robotic monitoring system has been carried out, providing a comparative evaluation against a conventional mesh of fixed sensors.

The LCA studies have been conducted in accordance with ISO 14040/14044 and are documented in dedicated Annexes. The results contribute to the SYMBIOSYST project's overarching objectives to minimize environmental impacts and to enable circular, high-performance agri-PV solutions.

The methodology and results presented in this deliverable will also serve as the fundamental basis for the Life Cycle Assessment of the SYMBIOSYST pilot installations, to be performed under Task 4.4, ensuring methodological consistency with the systems implemented in WP5.
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INTRODUCTION

1.1 DESCRIPTION OF THE DELIVERABLE CONTENTS

This deliverable summarizes the research activities carried out within Task 4.2 "Evaluate the environmental performance and resource circularity of the proposed systems" of the SYMBIOSYST project, under Work Package 4 (WP4) "Sustainable agri-PV", and presents the results of those activities from Task 4.1 "Design for sustainability and Eco-design" that were originally planned for Deliverable D4.1 "Eco-design requirements and guidelines for agri-PV" and have now been integrated into the present report.

The overall objective of WP4 is to address the sustainability aspects of agri-PV systems, guiding innovations developed in WP3 from the design phase with sustainability criteria, and assessing the environmental performance of the demo cases in WP5. WP4 includes dedicated activities on eco-design as well as on exploring the new opportunities that agri-PV brings to the food supply chain.

SYMBIOSYST as a project aims to foster the development of agri-PV-friendly technologies adaptable to plant variety, geography, and landscape, in order to maximize crop-electricity synergy (OBJ1), and to advance sustainable integration of these technologies across the value chain (OBJ2, OBJ3, OBJ4). A key transversal objective (OBJ5) is to minimize the Life Cycle Assessment (LCA) of novel agri-photovoltaic solutions, including the development of low-impact mounting structures, innovative PV modules, and synergies with the decarbonization of the food supply chain.

In line with this, the activities originally planned under Task 4.1 / Deliverable D4.1 focused on the definition and design of alternative PV module materials to improve eco-design (including the use of EU-made low-carbon cells, optimized frame design through FEM simulations, evaluation of non-fluorinated transparent backsheets, reliability testing, and sensitivity analysis on key design factors). The results of these activities are presented in Section 2 of this deliverable to ensure coherence and traceability within WP4, and to provide a comprehensive assessment of sustainable design pathways for agri-PV technologies.

In addition, part of the results presented in Section 3 — specifically the Life Cycle Assessment of mounting structures — have been developed in close collaboration with Task 3.1 "Innovative structures and PV modules for optimized light control in agri-PV systems" (led by CONVERT, with contributions from EFSOLARE, ENGIE-LAB, UPC, LAIMBURG, among others). This collaboration has been essential to advance the assessment of innovative structures (steel vs wood), and directly supports the decision-making process for Milestone MS4 "Use of wood for mounting structures".

In order to ensure methodological transparency, the Life Cycle Assessment (LCA) studies carried out under Task 4.2 have been conducted and documented separately, each following the standardized structure defined by ISO 14040/14044. The detailed inventory data, goal and scope definitions, system boundaries, and results for each subsystem (PV modules and structures, monitoring systems, crops, and integrated agri-PV configurations) are reported in dedicated Annexes to this deliverable. The main body of the document integrates and summarizes these results to provide a consolidated view of the environmental performance and circularity potential of the proposed SYMBIOSYST solutions.

The structure of this deliverable reflects this integrated approach:

- Section 2 presents the results of the Task 4.1 activities originally planned for D4.1;
- Section 3 presents the environmental performance and circularity assessment of the proposed solutions under Task 4.2, including results developed in collaboration with Task 3.1.

Together, these results contribute to the overarching goal of SYMBIOSYST to develop sustainable, circular, and high-performance agri-PV systems, supporting their broader adoption and impact.

1.2 REFERENCE MATERIAL

Not applicable.

1.3 ABBREVIATION LIST

Table 0.1. Abbreviation list

Table 0.1. Abbreviation list

Abbreviation	Meaning
Agri-PV	Agri-photovoltaics
CO_2 eq	Carbon dioxide equivalent
CTUh	Comparative Toxic Unit human
EF	Environmental Footprint
FU	Functional Unit
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MJ	Megajoule
MS	Milestone
PV	Photovoltaic
Pt	Points (as used in land use impact assessment)
Sb eq	Antimony equivalent
T	Task
WP	Work Package
kWh	Kilowatt-hour

DESIGN FOR SUSTAINABILITY AND ECO-DESIGN

This section presents the results of those activities from Task 4.1 "Design for sustainability and Eco-design" that were originally planned for Deliverable D4.1 "Eco-design requirements and guidelines for agri-PV" and have now been integrated into the present report. These activities focus on the definition and optimization of PV module materials and structural components to improve the eco-design and sustainability profile of agri-PV systems, without compromising technical performance or reliability.

The work includes:

- comparison of CO_2 footprint and other environmental impacts for EU-made silicon solar cells compared to cells made in China;
- the optimization of PV module frames through FEM simulations;
- the comparison of non-fluorinated transparent backsheets (that have improved recyclability) with fluorinated ones in terms of module performance, both before and after degradation induced by reliability tests;

These results contribute to the overall eco-design strategy of the SYMBIOSYST project, complementing the sustainability assessments performed in Section 3.

1.4 ENVIRONMENTAL COMPARISON EUROPE-MADE CELLS WITH CELLS PRODUCED IN CHINA

As a part of task 4.1 “Design for sustainability and Eco-design“, it was investigated how cells that have been produced in Europe compared to cells that have been produced in China. To choose the relevant countries, solar cell manufacturers were searched on the Solar Manufacturing Map of Solar Power Europe (see below).



Figure 0.1. Map indicating cell producers in Europe (2025). Source: online Solar Manufacturing Map (by Solar Power Europe). Meyer Burger cell production has been removed from this map manually, since this recent closing was not yet updated.

In June 2025, only 4 cell manufacturers are left in Europe. One of them is only making (non-silicon) solar cells for space applications (Azur Space in Germany), so should not be considered here. From the other ones, Oxford PV in Germany is making perovskite-silicon tandem cells, that are also not considered as a standard product and are only available in relatively small quantities. Also, the process flow is different from silicon solar cells. Taking this into account, only 2 silicon solar cell manufacturers are left in Europe, in Italy (3SUN) and Hungary (Ecosolifer). At the time the LCA for the silicon solar cells has been made, there were also still manufacturers in Germany and Finland, so those countries had also been taken into account. In addition, Turkey has still been taken into account since there is a significant cell production (by Kalyon PV) in that country close to Europe. Finally, Belgium was also taken into account for curiosity since imec is located in Belgium.

Several impacts of the solar cell manufacturing have been calculated using the Environmental Footprint 3.1 software from the European Commission. In the following graph, the impact on climate change is shown for different countries, for 1 m^2 area of silicon solar cells.

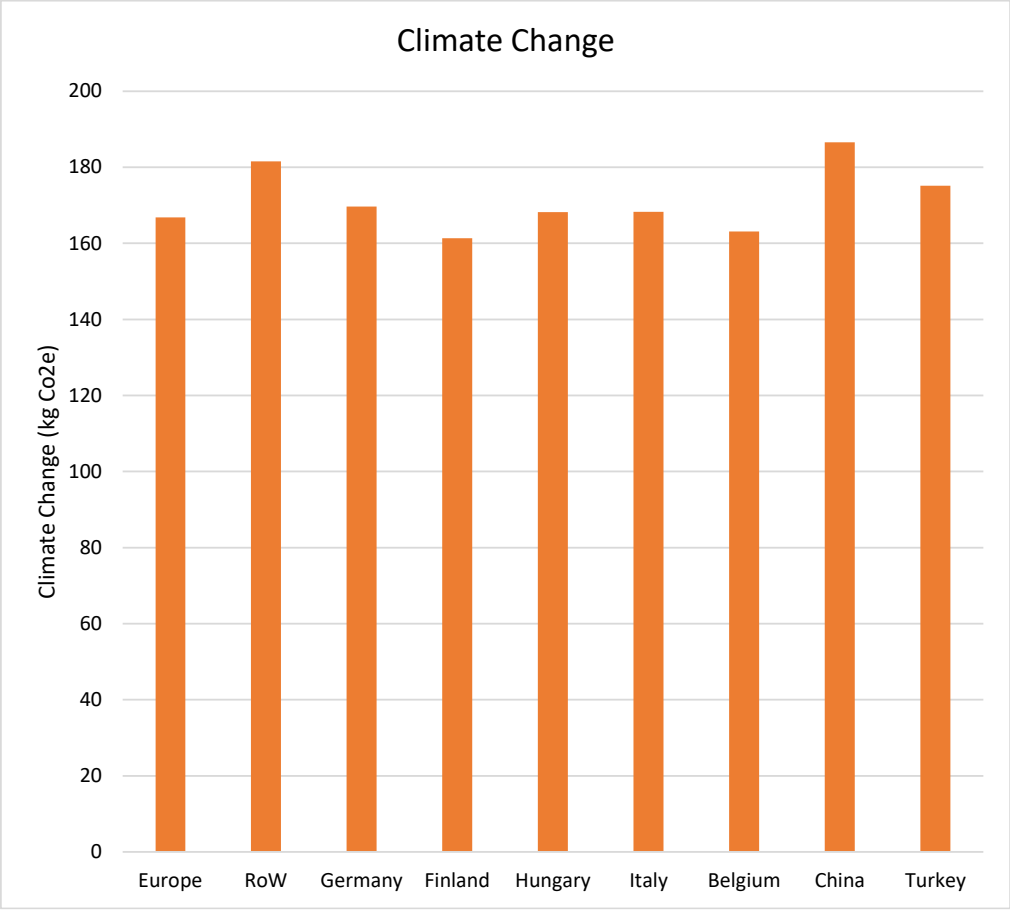


Figure 0.2. Impact on climate change for the production of 1 m^2 of crystalline silicon solar cells, for Europe as a whole, Rest of the World, individual European countries, China and finally Turkey.

The conclusion is that there is indeed some difference between the climate change for cells that have been manufactured in Europe compared to China, most likely due to the larger amount of coal-produced electricity in China. However, this difference is only around 11% between China and both Italy and Hungary, the 2

European countries where silicon solar cell production is still taking place. In Turkey, climate change is around 6% lower than in China.

For completeness, the other environmental impacts of silicon solar cell production are shown for individual European countries (each time in comparison to China) in the 3 graphs below. These results were also obtained using the Environmental Footprint 3.1 software.

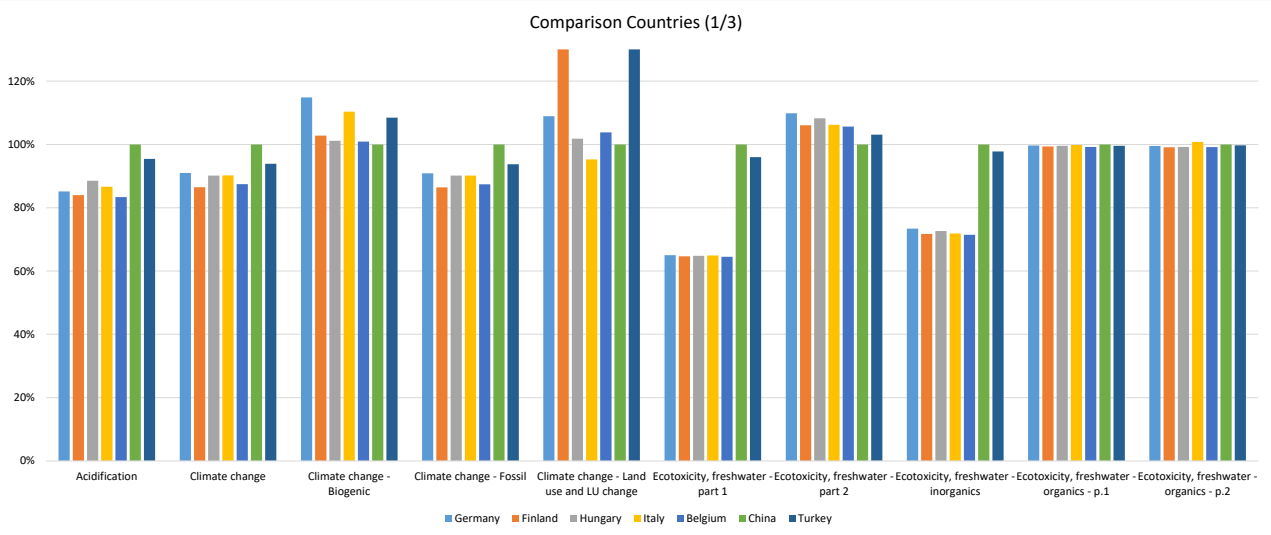


Figure 0.3. Comparison of environmental Impacts for the production of 1 m² of crystalline silicon solar cells, between China (green, considered to be 100%) and Germany, Finland, Hungary, Italy, Belgium and Turkey.

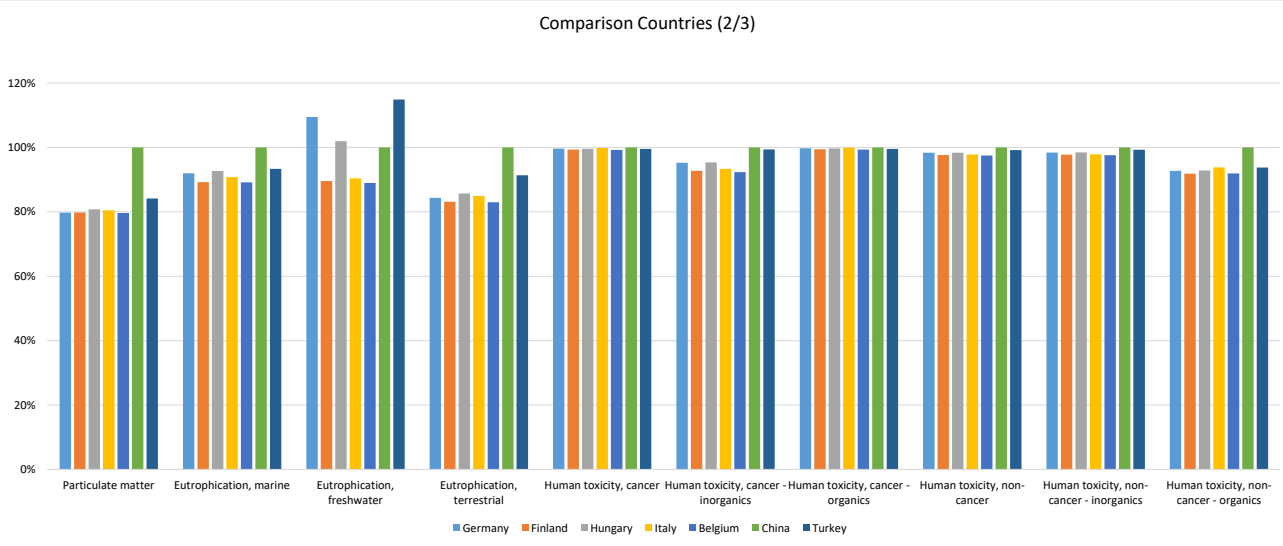


Figure 0.4. Comparison of environmental Impacts for the production of 1 m² of crystalline silicon solar cells, between China (green, considered to be 100%) and Germany, Finland, Hungary, Italy, Belgium and Turkey.

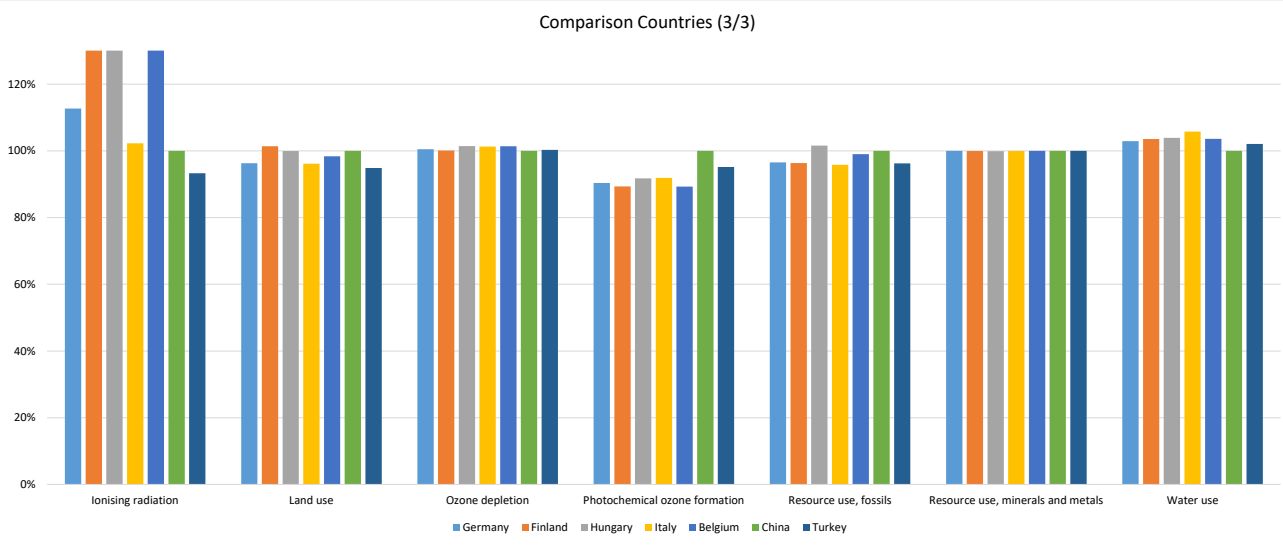


Figure 0.5. Comparison of environmental Impacts for the production of 1 m² of crystalline silicon solar cells, between China (green, considered to be 100%) and Germany, Finland, Hungary, Italy, Belgium and Turkey.

For a few environmental impacts, production of silicon solar cells in a certain European country (or Turkey) has a higher impact than in China, but most of the time the impact is a bit lower in Europe. The differences with China are usually within 20%, except for the fresh water ecotoxicity, both for part 1 and inorganics. In these cases, the difference between China and the European countries is ~35% (part 1) or ~25% (inorganics), the higher impact being for China.

To summarise the results, the production of silicon solar cells in Europe has in general a somewhat lower environmental impact than production in China. Hower, differences are not very large. For the impact on climate change in particular, it is ~11% lower than in China for the 2 European countries where silicon solar cells are still being produced today (June 2025).

1.5 FINITE ELEMENT MODELING (FEM) ANALYSIS FOR STEEL PV MODULE FRAME (INSTEAD OF ALUMINIUM FRAME)

1.5.1 ENVIRONMENTA ARGUMENTS FOR USING STEEL AS MODULE FRAME MATERIAL

Anodised extruded aluminium profiles have been used since a long time as the standard material for the frame around PV modules. It does not corrode and has a low density. However, the energy required for the manufacturing of such profiles is quite high. For this reason, as an alternative, rolled steel frames have been proposed (for steel frames extrusion is not used as manufacturing method), for example by Origami Solar in the USA. In the figure below, the Greenhouse Gas footprint for steel frames is compared to the footprint of extruded aluminium frames.

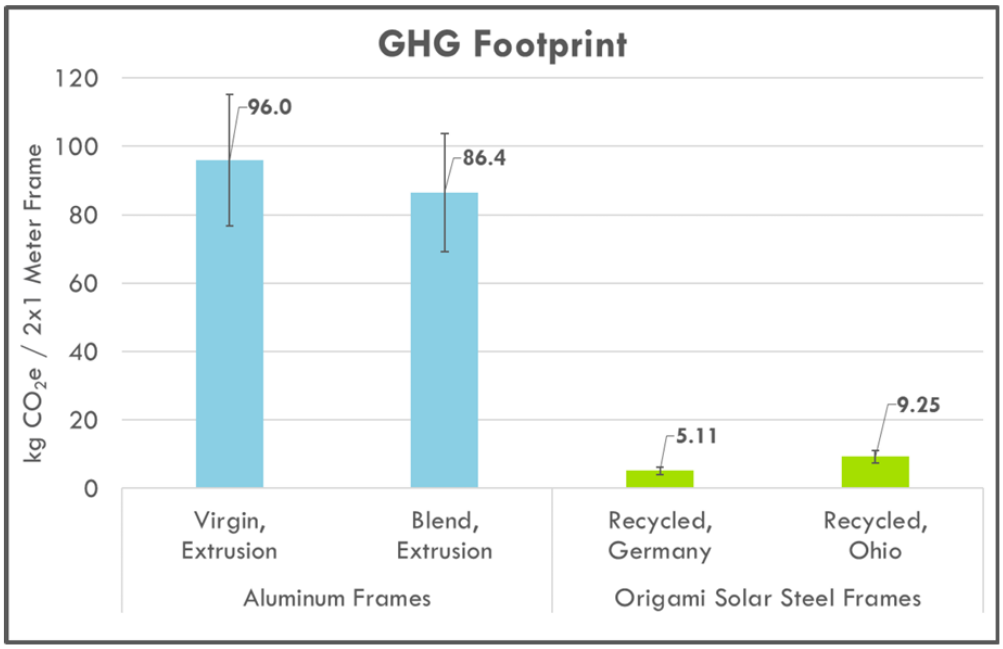


Figure 0.6. Comparison Greenhouse Gas footprint for aluminium and steel frames, per module of 2x1 m. Source: Origami Solar Environmental Impact Report prepared by "Boundless impact research and analytics"

For this reason, in this finite element modelling, steel has been taken as the frame material. It should be mentioned that the steel frames are covered with an anti-corrosion alloy to ensure a long lifetime of the frame.

1.5.2 SIMULATION

To calculate the resulting first principal stress within the PV module, the "Solid Mechanics" module was employed. The simulated PV module had dimensions of 1670 mm × 990 mm. For simplification purposes, the module was modelled as a layered shell consisting of glass – encapsulant – cells – encapsulant – polymeric backsheet. This approach is considered sufficient since the analysis focuses solely on stationary conditions at a constant temperature, without accounting for the viscoelastic behaviour of the encapsulant.

Interactions between layers, such as adhesion defects, were not included due to the lack of precise data. The encapsulant was represented by an Ethylene Vinyl Acetate (EVA) layer, while the backsheet was modeled as a Tedlar-Polyethylene Terephthalate-Tedlar (TPT) structure. The glass layer was assigned a thickness of 3.2 mm. The layered shell was connected to the silicone edge sealant and the frame by assuming continuity.

Three simulation scenarios were conducted: one with an aluminium frame (see cross-section in Figure 2.7 (a)), one with a steel frame of the same geometry, and one with a steel frame featuring a modified cross-section (Figure 2.7 (b)). The main mechanical properties used in the simulations are presented in Table 2.1. The module was constrained along its shorter sides, and a pressure load of 2400 Pa was applied to the front surface. The effect of gravity was also included.

To reduce computational complexity, symmetry was assumed, so that only half of the PV module had to be modelled (Figure 2.8). Finally, a customized mesh was generated based on computational requirements, and a "Stationary Study" was carried out.

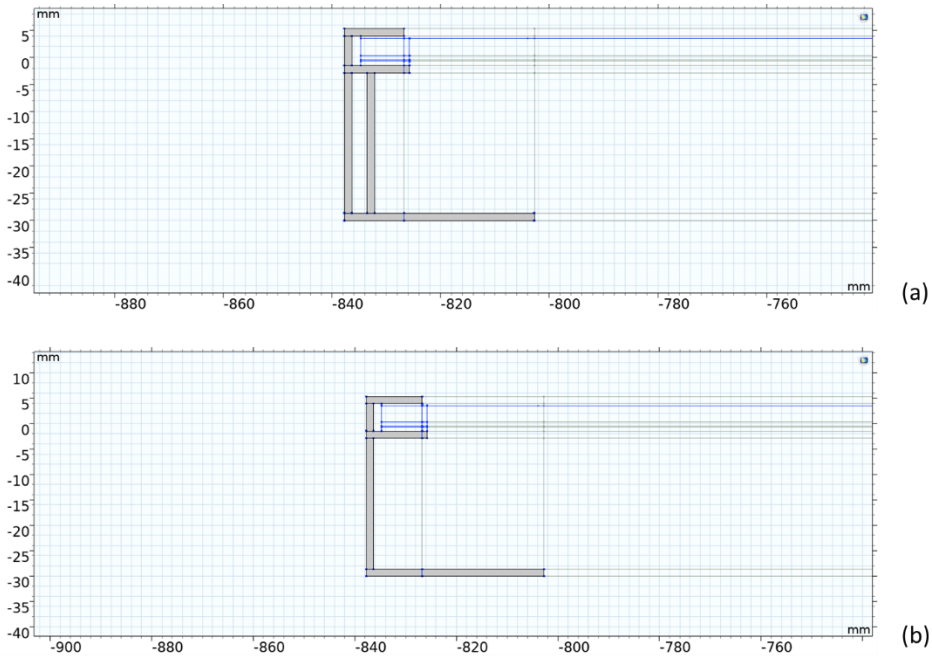


Figure 0.7. Cross-section for (a) standard aluminium and steel and (b) modified steel frames

Table 0.1. Material properties

Materials	Model	Thickness (mm)	Density (kg m^{-3})	Young's Modulus (Pa)	Poisson's Ratio
Float Glass	Linear Elastic	3.2	2220	$73.7 \cdot 10^9$	0.168
Silicon (cells)	Linear Elastic	0.160	2329	$170 \cdot 10^9$	0.28
EVA (encapsulant)	Linear Elastic	0.4	1760	$16.9 \cdot 10^9$	0.4995
Silicone (edge sealant)	Linear Elastic	See [1]	1310	$1 \cdot 10^6$	0.49
TPT (backsheet)	Linear Elastic	0.2	980	$2.9 \cdot 10^9$	0.24
Aluminium Frame	Linear Elastic	See Figure 2.7	2700	$69 \cdot 10^9$	0.33
Hardened Steel Frame	Linear Elastic	See Figure 2.7	7850	$200 \cdot 10^9$	0.30

[1] https://doi.org/10.1016/j.engstruct.2024.118760

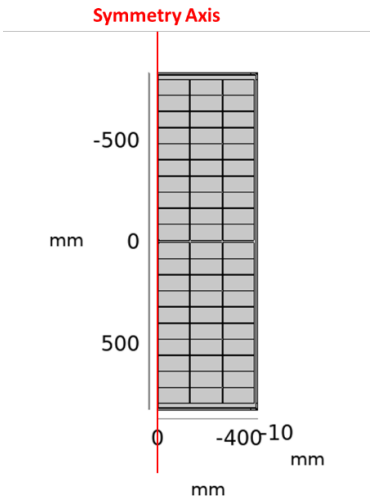


Figure 0.8. Full geometry and symmetry axis for the simulations

1.5.3 RESULTS

Figure 2.9 and Figure 2.10 present the distribution of first principal stress normalised over the tensile strength of the represented material, on both the front and rear sides of the photovoltaic (PV) module frame for three configurations: aluminium, steel, and steel with a modified cross-section. The tensile strength of the aluminium was considered equal to 290 MPa, while the one of hardened steel equal to 1500 MPa.

On the front side of the frame, stress concentrations are predominantly located along the attached edges, with particularly elevated values observed at the corners. In the case of the steel frame with a modified cross-section, the peak stress shifts towards the inner corners. This deviation is attributed to the absence of additional reinforcement elements, which are present in the unmodified steel configuration.

Among the three designs, the aluminium frame exhibits the highest normalised first principal stress, followed by the steel frame with a modified cross-section. The standard steel frame demonstrates the most favourable mechanical performance. The maximum first principal stress values for the aluminium, steel, and modified steel frames are 0.9, 0.28, and 0.52, respectively. It is important to note that these values may be overestimated due to limitations in the meshing process; further investigation is required to determine whether the peak values represent actual stress concentrations or numerical artifacts.

On the rear side of the frame, the highest first principal stress is concentrated at the midpoint of the longest edge. Consistent with the front-side results, the aluminium frame experiences the greatest stress, followed by the steel frame with a modified cross-section.

Deformation analysis (Figure 6) reveals that maximum displacement also occurs at the centre of the longest edge of the frame. The measured deformations are 25 mm for the aluminium frame, 18 mm for the steel frame, and 20 mm for the steel frame with a modified cross-section.

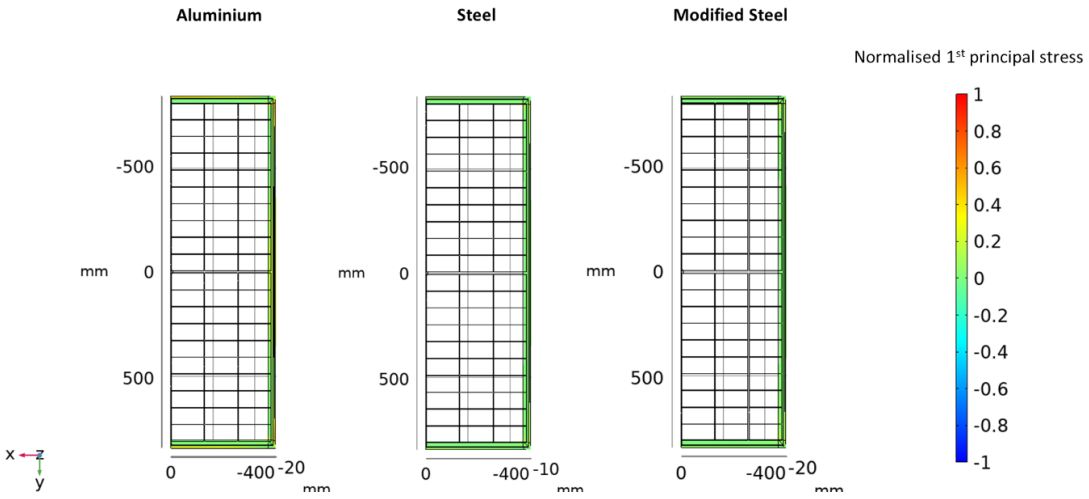


Figure 0.9. Distribution of first principal stress normalised over the tensile strength of the represented material, on the front side of the PV module frame for three configurations: aluminium, steel, and steel with a modified cross-section

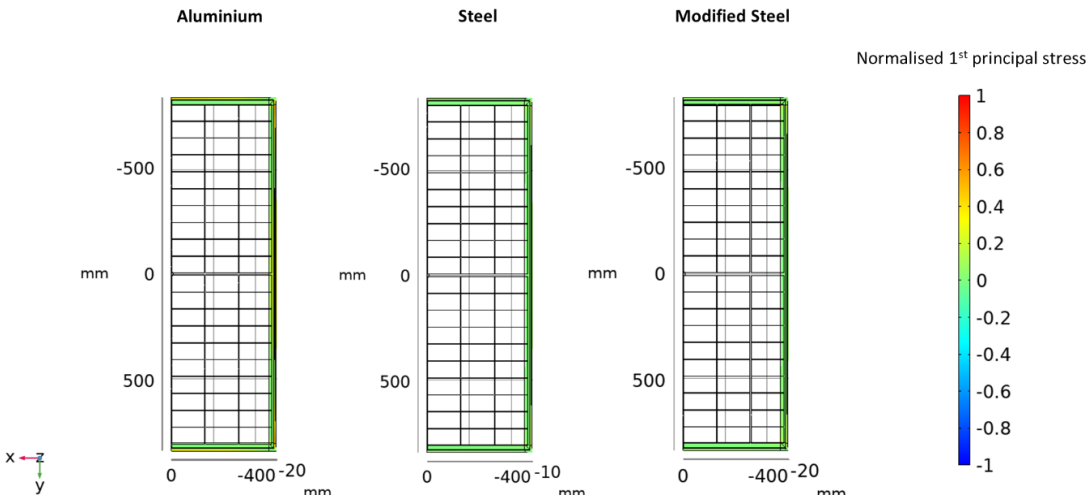


Figure 0.10. Distribution of first principal stress normalised over the tensile strength of the represented material, on the rear side of the PV module frame for three configurations: aluminium, steel, and steel with a modified cross-section.

With respect to stress transfer to the PV modules, the results indicate that steel frames—regardless of configuration—outperform aluminium frames. For all tested modules, the front glass (Figure 2.12) consistently experiences higher first principal stress compared to the polymeric backsheet (Figure 2.13). These stress concentrations are primarily located near the attached short edges of the PV modules and vary depending on the frame material and design.

The highest stress in the front glass is observed in the module with the aluminium frame, reaching 86 MPa. In contrast, the lowest stress is recorded in the module with the steel frame featuring a modified cross-section (64 MPa), followed by the standard steel frame (79 MPa). This improved performance is likely due to the enhanced flexibility of the modified steel frame, which permits greater deformation of the PV module (67 mm, Figure 6). Such deformation may help alleviate stress concentrations in the front glass.

The aluminium frame results in almost the same overall deformation as the steel frame with modified cross-section, while the standard steel frame exhibits the least (56 mm). Although the findings suggest that the modified steel frame offers improved stress distribution within the glass layer, further analysis is necessary to assess its impact on the other PV module components.

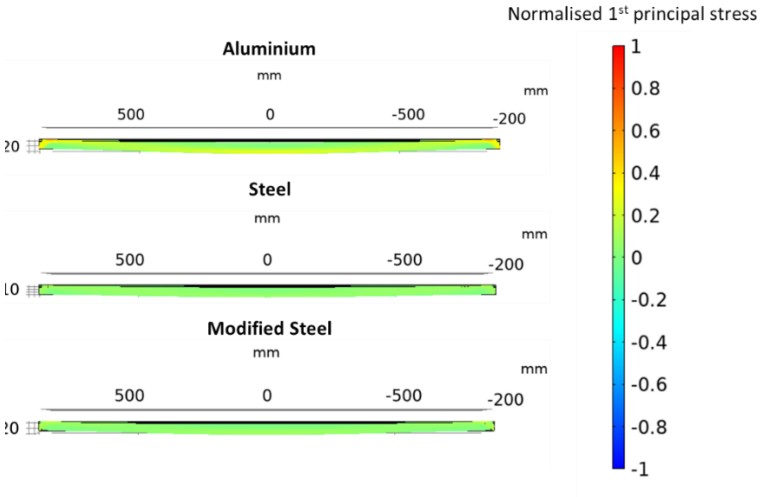


Figure 0.11. Distribution of first principal stress normalised over the tensile strength of the represented material and deformation of the PV module frame for three configurations: aluminium, steel, and steel with a modified cross-section

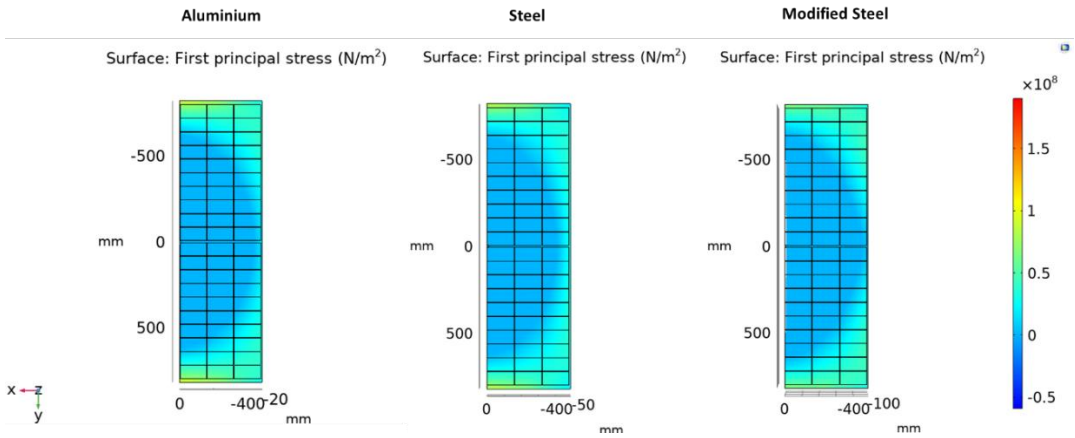


Figure 0.12. Distribution of first principal stress on the front glass of the PV module for three configurations: aluminium, steel, and steel with a modified cross-section.

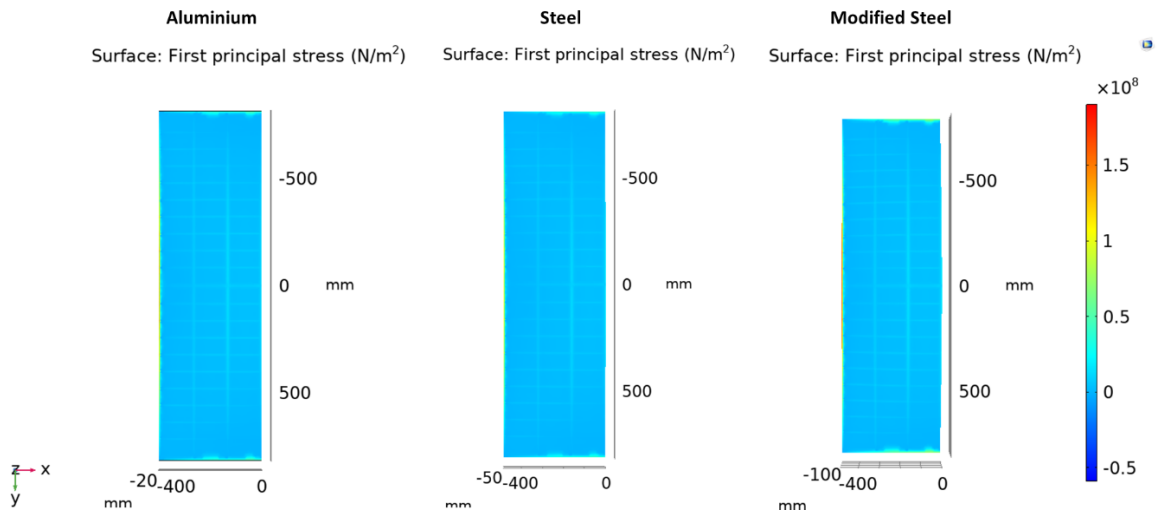


Figure 0.13. Distribution of first principal stress in the backsheet of the PV module for three configurations: aluminium, steel, and steel with a modified cross-section.

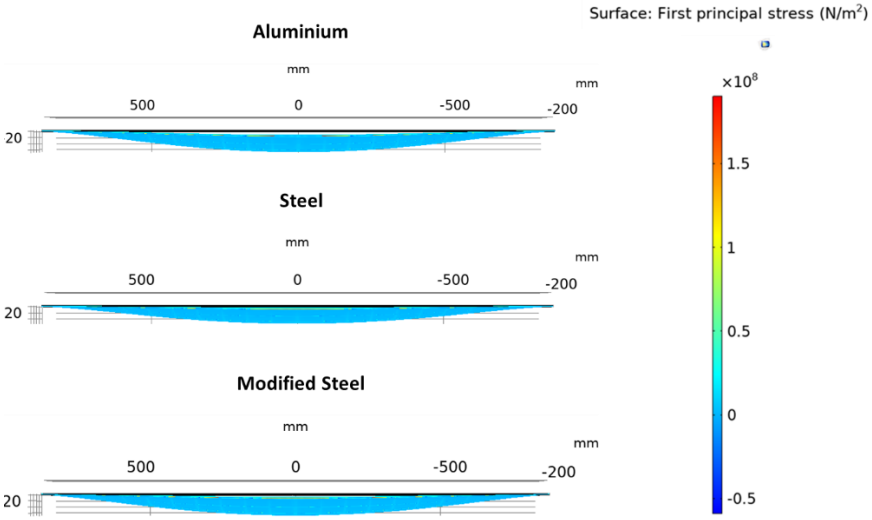


Figure 0.14. Distribution of first principal stress on the rear backsheet and deformation the PV module for three configurations: aluminium, steel, and steel with a modified cross-section

To summarise, replacing aluminium by steel in PV module frames not only offers around 90% reduction in greenhouse gas footprint, but also better mechanical performance. Under a uniform pressure, the stress values reached in the modelled steel frames stay further away from the maximum tensile stress, the deformation of the frame is more limited and the stress distribution in the module's front glass is also improved (less differences) compared to aluminium. Considering these advantages, replacing aluminium by steel seems to be very promising.

1.6 RELIABILITY TESTS ON MODULES HAVING TRANSPARENT BACKSHEETS WITH/WITHOUT FLUOR

1.6.1 INTRODUCTION ABOUT BACKSHEETS WITH/WITHOUT FLUOR

Historically, polymer layers containing fluor have usually been applied in the back sheet of PV modules because of their very good resistance against weathering. Typically, such a back sheet is composed of 3 layers, bonded together using an adhesive. The famous abbreviation for such a back sheet composition is TPT (which stands for Tedlar-PET-Tedlar). Tedlar is the brand name of the company Dupont for polyvinyl fluoride, while PET stands for polyethene terephthalate. This inner layer made of PET is used to provide strength and electrical protection (since the back sheet has to withstand voltage a voltage difference of up to 1000-1500 V). An alternative fluor containing material used as layer in PV backsheets is PVDF (polyvinylidene fluoride). This material contains even more fluor as PVF, it is a bit cheaper than PVF but has a bit lower UV resistance. Because of the lower cost, nowadays it is used more frequently in back sheets than PVF. Over the last 15 years, also other types of back sheets have been developed to reduce costs and to avoid the use of fluor in back sheets. This is because the presence of fluor can lead to problems for recycling and environmental pollution after the modules have reached end-of-life. When recycling PV modules by thermal treatment, dangerous fluor containing gases are formed when fluorinated backsheet is present in the modules.

1.6.2 DESCRIPTION OF MATERIALS AND RELIABILITY TESTS

Agri-PV modules are typically bifacial, and are using either a glass plate or transparent backsheet at the rear side. For this reason, for the SYMBIOSYST project it has been investigated how modules with a non-fluorinated transparent backsheet performs initially and after reliability testing compared to a fluorinated type, while glass-glass modules have been used as reference modules.
The modules were tested for reliability for up to 600 thermal cycles (of 3 hours each) between temperatures of -40 °C and 85 °C (temperature cycles as specified in IEC 61215) and damp heat testing up to 6000 h at 85 °C/85% relative humidity (temperature and humidity as specified in IEC 61215).

The silicon cells that have been used in the modules were monocrystalline silicon bifacial PERC cells, 156 mm x 156 mm in size with 4 busbars. The mini-modules have been made with glass plates of 190 mm x 190 mm in size and a thickness of 3.2 mm. The encapsulant used was EVA, lamination temperature was 147 °C.
The fluor containing transparent back sheet is of the “TPT” type, it has a layer of 25 μm PVF on the air side, a 320 μm PET layer as the core material and a 10 μm PVF layer on the encapsulant side. On the backsheet, white stripes have been added to increase the module current. The stripes have to be aligned with the spacings in between the cells so that light incident on these spacings is partially back-reflected within the module, so that the light intensity at the cell edges is increased. However, since full cells have been used in these mini-modules, and since the pattern of white stripes had been designed for half-cells, there is one stripe across the centre on the rear side of the module that should normally not be there, but it does not harm for the relative comparisons in the reliability experiments.
The transparent back sheet without fluor was composed of a 30 μm polypropene layer on the air side, a 290 μm polypropene copolymer as the core material and a layer of 30 μm polyethene copolymer on the encapsulant side.

Pictures of the different modules, taken from both front and rear side, are shown in the figure below.

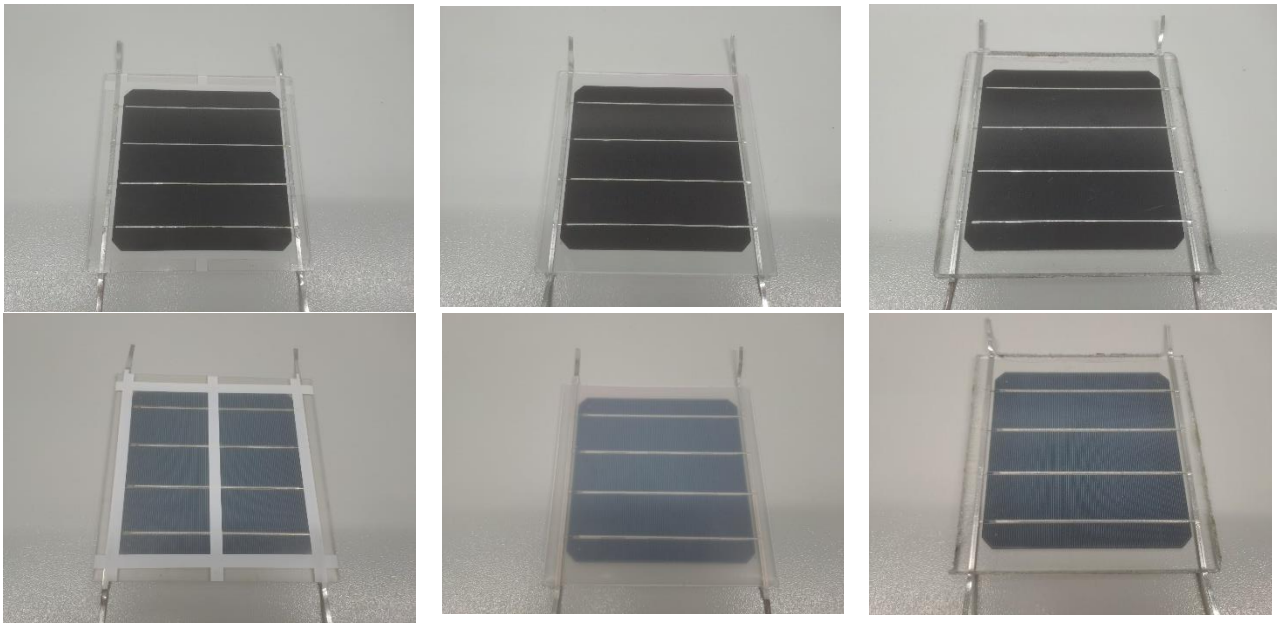


Figure 0.15. Pictures of the modules with transparent back sheet with fluor (left), without fluor (centre) and with glass at the rear side (right) for both front side (top) and rear side (bottom). As mentioned in the main text above, there is also a useless white stripe at the centre of the rear side for the fluor back sheet since it was normally intended for modules with half cells.

1.6.3 GENERAL OBSERVATIONS AFTER MODULE LAMINATIONS

No difficulties were observed for the lamination for both transparent back sheets (and glass-glass modules). The power "bifaciality" factor (defined as Pmax,rear/Pmax,front) was a bit lower for the transparent back sheet modules (70.6% without fluor, 67.3% with fluor) than for glass-glass (72.5%). However, this is a rather minor issue given that the rear side contribution for yearly yield is typically only 10% compared to the contribution of the front side. That the power bifaciality factor was lowest for the fluorinated one is also logical, given the presence of the white stripe at the centre of the rear side of the module. In electroluminescence (EL) pictures, no (major) cell defects were observed, as can be observed in some example pictures that are shown below.

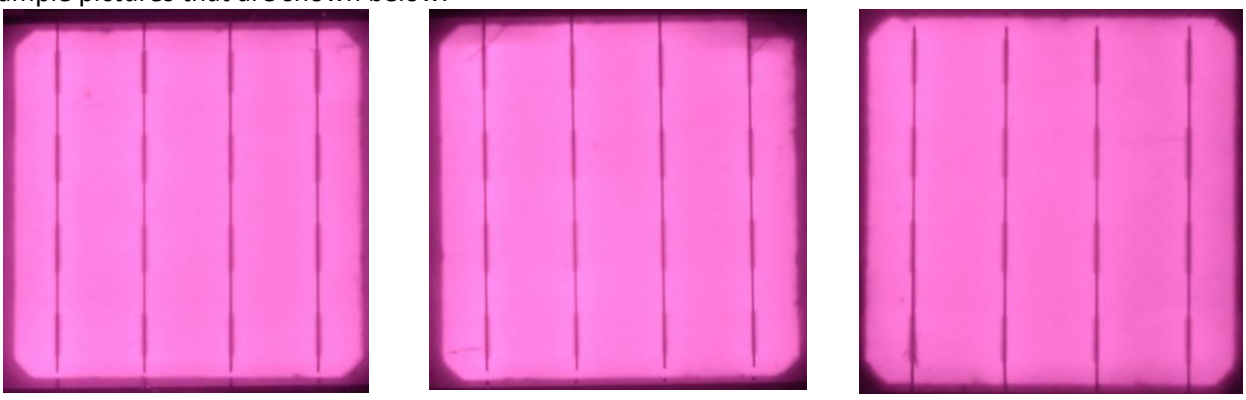


Figure 0.16. EL pictures of the modules with transparent back sheet with fluor (left), without fluor (centre) and for glass-glass (right).

1.6.4 RESULTS OF DAMP HEAT TESTING

In the following figure, in the upper left graph the relative change in Pmax as a function of the duration of the damp heat testing at 85 °C/85% relative humidity is shown. In the other graphs, the changes in Isc, Voc and FF are shown as well. The total test duration has been 6000 h, which is 6 times the requirement in IEC 61215.

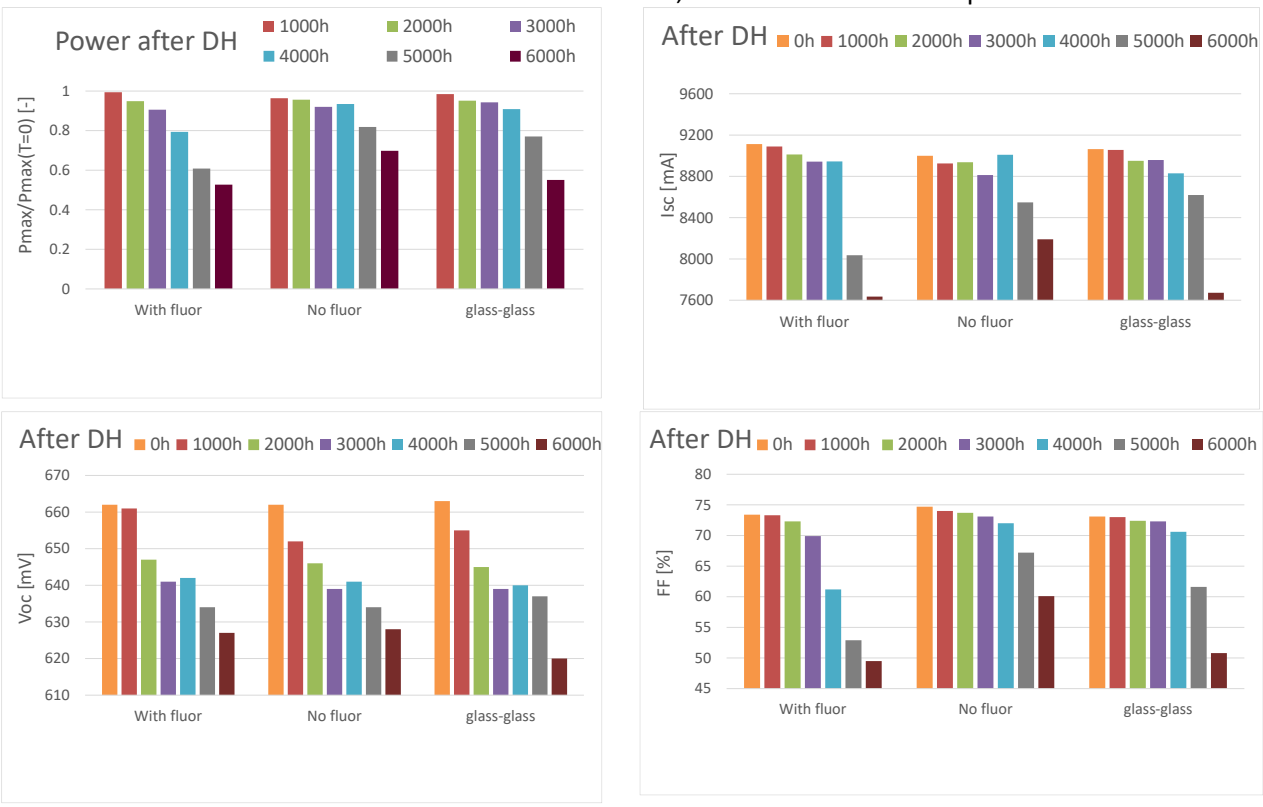


Figure 0.17. Evolution of power, Isc, Voc and FF as a function of the duration of damp heat testing for the modules with transparent back sheet with fluor, transparent back sheet with no fluor and glass-glass

The power degradation graph shows that all materials pass the IEC criterion of < 5% power degradation after 1000 h. The backsheet without fluor shows a power degradation of 3.4%, while there is 0.6% power loss for the fluorinated back sheet and 1.6% for glass-glass. It appears that the power loss for the non-fluor back sheet after 1000 h is for a large part (1.5%) due to Voc loss, although the power loss in DH testing is usually more related to FF loss. Looking at the Voc degradation after prolonged testing, we see that fluor/non-fluor back sheets are behaving very similar in terms of Voc degradation. If we look at the remaining module power after longer damp heat testing, it is clear that the back sheet without fluor outperforms the fluorinated back sheet. Finally, in the EL pictures below, it can be observed that the degradation takes place near the busbars.

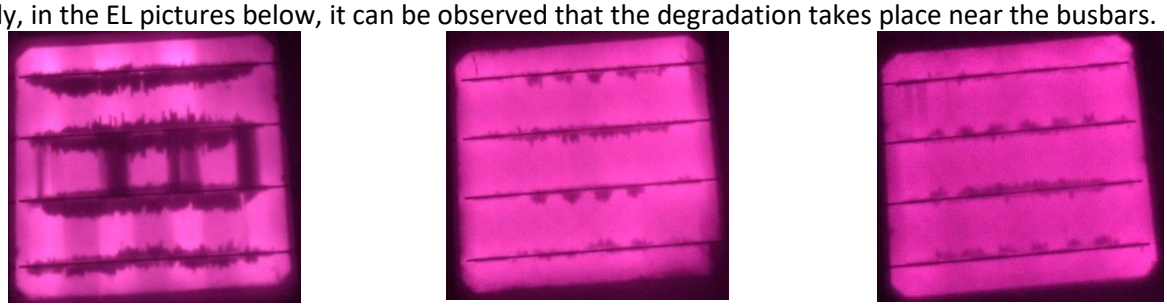


Figure 0.18. EL pictures of the modules with transparent back sheet with fluor (left), without fluor (centre) and for glass-glass (right) after 4000 h of damp heat testing.

1.6.5 RESULTS OF THERMAL CYCLING TESTING

In the following figure, in the upper left graph the relative change in Pmax as a function of the number of thermal cycles is shown. In the other graphs, the changes in Isc, Voc and FF are also shown. For the IEC 61215 certification 200 thermal cycles (TC) are required, here the testing has been done for up to 600 TC, so 3 times more than required. The degradation criterion for passing IEC 61215 certification is < 5% power loss after 200 TC.



Figure 0.19. Evolution of power, Isc, Voc and FF as a function of the number of thermal cycles for the modules with transparent back sheet with fluor, transparent back sheet with no fluor and glass-glass

From the upper left graph that shows the remaining power, it is clear that all materials would have passed IEC 61215 certification. The glass-glass one is even doing the worst in this test after 200 TC. The back sheet without fluor shows around 3% power loss after 200 TC, which is quite acceptable. The increase of module powers (compared to the 200 TC values) after 400 TC and 600 TC is a bit atypical. When looking into the data for the other I-V parameters, it can be noticed that both Voc and FF still show a gradual decrease after 400 TC and 600 TC that could be expected. However, since the Isc values increase significantly after 400 TC and especially 600 TC, the losses in Voc and FF are overcompensated, leading to an increase of the module powers after 400 TC and 600 TC. The reason for the Isc increase is unclear, most likely related to intensity calibration. Finally, the EL images do not show clear problematic regions, except for glass-glass where it seems that the strips on the busbars lost connection close to the edges.

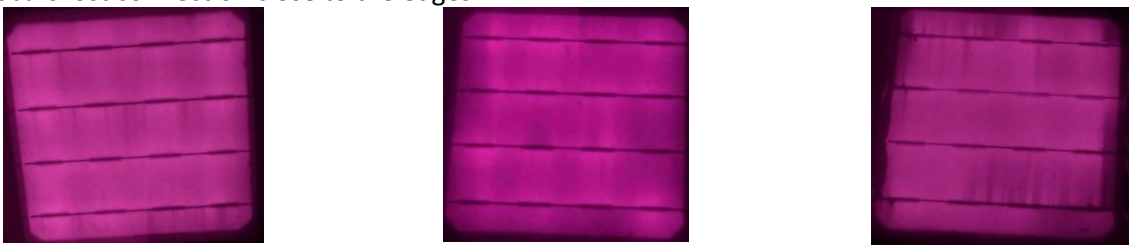


Figure 0.20. EL pictures of the modules with transparent back sheet with fluor (left), without fluor (centre) and for glass-glass (right) after 600 thermal cycles

1.6.6 FINAL CONCLUSIONS BACKSHEET WITH/WITHOUT FLUOR

Based on the results of the damp heat test and the thermal cycling test, it was found that the transparent fluor-free polypropene based backsheet investigated in this task performs at least as good, or even better, than the transparent TPT type back sheet that contains 2 outer layers of polyvinyl fluoride material.

ENVIRONMENTAL PERFORMANCE AND CIRCULARITY ANALYSIS

This section presents the Life Cycle Assessment (LCA) of selected technologies developed within the SYMBIOSYST project, as part of Task 4.2 "Evaluate the environmental performance and resource circularity of the proposed systems" under WP4 "Sustainable agri-PV".

The objective of this analysis is to provide a quantitative assessment of the environmental impacts and circularity potential of key innovations proposed in SYMBIOSYST, applying standardized LCA methodology in accordance with ISO 14040/14044 and the European Environmental Footprint (EF 3.0) method. The results aim to support eco-design decisions, inform the sustainability assessment of integrated agri-PV systems, and contribute to the broader objectives of the project in terms of minimizing environmental impacts (OBJ5).

The technologies addressed in this assessment are summarized below:

Table 0.1. SYMBIOSYST technologies

Technology component	Description	LCA status in this deliverable
Mounting structures + PV modules	Multifunctional tracker system + PV modules (standard and semi-transparent) Analysis of wood or steel	Included
Monitoring system (robot)	Autonomous robot for environmental monitoring	Included
Digital services	Digital platform, data analytics, operation and maintenance services	Not included

The LCA of mounting structures + PV modules and of the robotic monitoring system have been conducted and are presented in the following sections, with detailed inventory data and impact results documented in the corresponding Annexes.

Regarding the digital services, the LCA has not been performed at this stage. This is due to the current lack of a finalized and operational deployment of the digital platform, as well as the high dependence of its environmental impacts on factors such as the specific cloud infrastructure, data center locations, and user models. Conducting a robust and representative LCA of the digital services will therefore be more appropriate once the platform is fully specified and implemented in the project demos. This approach is consistent with good LCA practice, which avoids speculative or incomplete modelling of systems still under development.

A specific focus of the analysis is the comparative assessment of wood vs steel mounting structures, which directly supports the decision process for Milestone MS4 "Use of wood for mounting structures". This analysis has been developed in collaboration with Task 3.1 "Innovative structures and PV modules for optimized light control in agri-PV systems", leveraging the technical designs and material data generated within T3.1.

The general system model and functional units considered for the Life Cycle Assessment of the SYMBIOSYST technologies are presented in Figure X.1. The model defines the boundaries of the system ("cradle to grave") and the main components included in the assessment: mounting structures + PV modules, robotic monitoring system, and crops. The digital services component has not been included in the LCA at this stage, as explained earlier.

Although the crops component is not directly required for the scope of this deliverable (D4.2), it is included in the overall system model to provide a complete representation of the agr-PV system interactions and to maintain consistency with the broader sustainability assessments performed in the project.

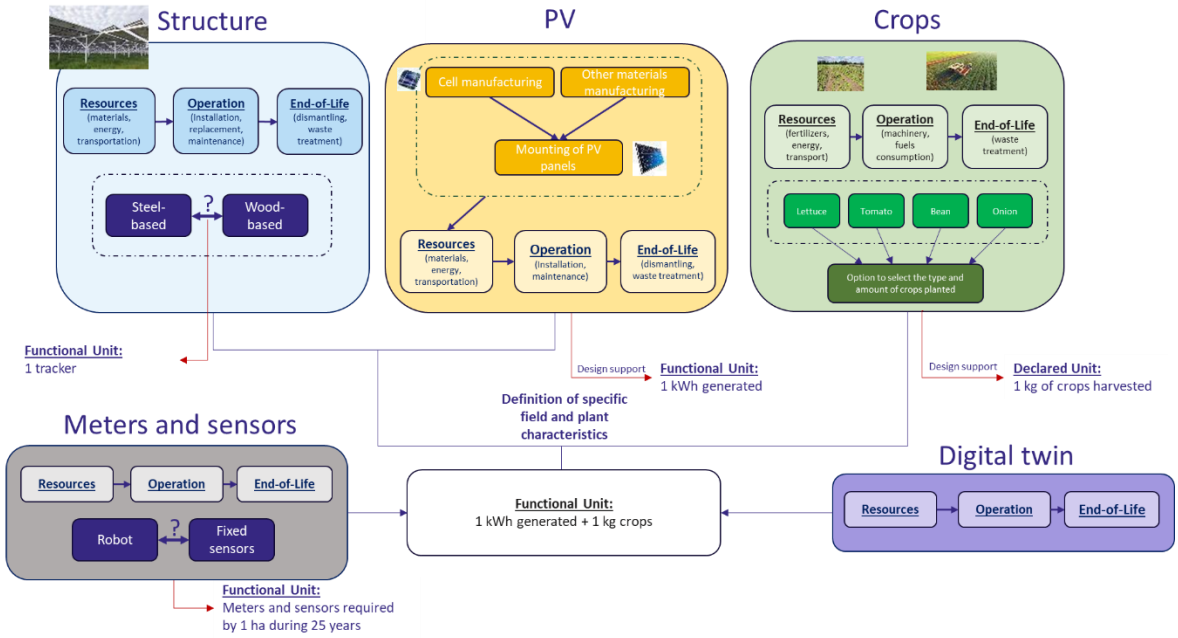


Figure 0.1. Overview of the SYMBIOSYST system model and functional units considered for the LCA

The LCA results presented in this section are structured as follows:

- Section 3.1: Mounting structures, with a specific focus on the comparative analysis of wood vs steel structures, developed in collaboration with Task 3.1, and supporting Milestone MS4.
- Section 3.2: PV modules presents the comparative performance of the two PV module configurations under the full system perspective, combining structure and modules with functional performance.
- Section 3.3: Monitoring systems (robot).

1.7 MOUNTING STRUCTURES

This section presents the Life Cycle Assessment (LCA) of the mounting structures and PV modules of the SYMBIOSYST system. The analysis has been carried out according to the methodology defined by ISO 14040/14044, applying the EF 3.0 method as used throughout the LCA activities in WP4, and is fully documented in Annex 1 of this deliverable.

The scope of this LCA includes the multifunctional tracker structures and the associated PV modules, both in standard opaque and semi-transparent configurations. The analysis considers the entire cradle-to-grave life cycle of these components, with the aim of providing a robust basis for eco-design decisions and informing the overall sustainability evaluation of the SYMBIOSYST agri-PV system.

A specific focus of this analysis has been the comparison between steel-based and wood-based mounting structures, in support of the decision process for Milestone MS4 "Use of wood for mounting structures". This comparative assessment was developed in close collaboration with Task 3.1, which contributed the technical design data and material specifications for the innovative mounting structures assessed.

In addition to the environmental LCA, the analysis has also considered resource availability, supply chain aspects, and technical feasibility of the wood-based solutions, as documented in the dedicated "Wood analysis" report (Annex to this deliverable). This complementary analysis provides essential context to interpret the LCA results and to support an informed Go/No-Go decision for MS4.

The following configurations have been assessed:

- Steel-based structure (baseline scenario)
- Steel-based structure with extended lifetime (reuse scenario, 60 years)
- Wood-based structure without replacement (optimistic scenario)
- Wood-based structure with replacement after 15 years
- Wood-based structure with protective coating (preventive maintenance scenario)

1.7.1 KEY RESULTS

The results of the LCA show that wood-based structures can offer substantial environmental advantages compared to conventional steel-based structures, particularly in terms of climate change impacts and resource use.

In scenarios where appropriate maintenance strategies are implemented (either through scheduled replacement or protective coating), wood-based structures achieve lower global warming potential (GWP), reduced fossil resource consumption, and lower impacts on mineral and metal resource use.

However, trade-offs are also observed. As expected, land use impacts are significantly higher for wood-based structures due to the use of timber as a primary material. Additionally, certain indicators such as particulate matter formation, human toxicity, and water use exhibit more variable results, depending on the specific scenario considered.

In particular, the increase in particulate matter formation observed in wood-based scenarios (up to 129%) is primarily due to the use of glued laminated timber (glulam), whose production involves intensive wood processing steps — including lamination and adhesive application — which significantly contribute to emissions in this category, as detailed in Annex 1.

The reuse scenario for steel-based structures (assuming a 60-year lifetime) also demonstrates substantial environmental benefits compared to the baseline, particularly for GWP and resource use, although it does not achieve the same reductions as the optimized wood-based configurations.

The following table summarizes the key impact categories for the different configurations (values are per functional unit, 1 tracker):

Table 0.2. Summary of main LCA impact indicators for mounting structure configuration (Data extracted from Annex 1, Table 19)

Configuration	Climate Change (kg CO_2 eq)	Land use (Pt)	Resource use, fossils (MJ)
Steel (baseline)	1,189.3	7,088	16,213.0
Steel (reuse 60y)	763.1	4,762	10,556.8
Wood (no replacement)	893.6	140,460	12,867.3
Wood (15y replacement)	1,150.1	277,051	16,890.6
Wood (coating)	972.0	142,058	13,677.2

To provide a visual comparison of the overall performance across multiple impact categories, Figure 3.2.1 presents a radar chart illustrating the relative impacts of the different configurations, normalized to the baseline steel scenario.

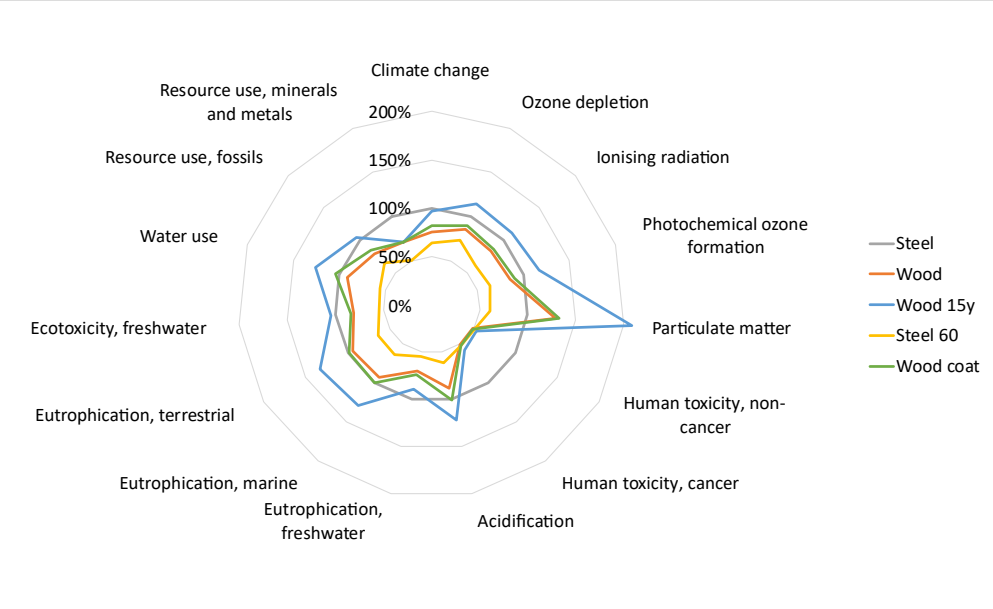


Figure 0.2. Relative impacts of mounting structure configurations (steel vs wood scenarios) (Adapted from Annex 1, Figure 6)

1.7.2 INTERPREATION AND CONCLUSIONS

The results confirm that wood-based structures represent a promising solution from an environmental perspective, provided that appropriate design and maintenance strategies are implemented to ensure long-term durability and performance. The reuse scenario for steel structures also remains a viable eco-design option.

The availability of suitable wood resources, as well as the feasibility of large-scale implementation, must be carefully considered, as discussed in the complementary Wood analysis Annex. In this context, the integrated assessment presented here provides critical input to the MS4 Go/No-Go decision and supports the ongoing eco-design optimization of the SYMBIOSYST system.

1.8 PV MODULES: STANDARD VS SEMI-TRANSPARENT CONFIGURATIONS

This subsection presents the Life Cycle Assessment (LCA) results for the two PV module types considered in the SYMBIOSYST agri-PV system: standard opaque modules and semi-transparent modules with partial cell coverage (~60%). The assessment follows the same methodology (ISO 14040/14044, EF 3.0 method) as the mounting structures, and full details are available in Annex 1.

The goal of this analysis is to compare the environmental performance of both PV module configurations over their full life cycle — including manufacturing, operation (with assumed replacement rates), and end-of-life treatment — and to support decision-making regarding PV technology selection in agri-PV applications.

The comparison is based on a functional unit of 1 kWh of electricity generated over a 30-year operational period, under typical conditions in the Barcelona region (Baix Llobregat).

1.8.1 KEY RESULTS

The LCA results show that semi-transparent modules have lower environmental impacts than standard opaque modules in most impact categories, particularly in climate change, resource use, and water consumption. These improvements are mainly due to the reduced material intensity of semi-transparent modules, which contain fewer silicon cells and less aluminium per unit area.

However, this reduction in environmental burden is partially offset by a lower electricity yield, a factor that must be considered when evaluating overall system performance.

The table below presents selected impact indicators for both module types, per kWh of electricity generated:

Table 0.3. Summary of main LCA impact indicators for mounting structure configuration (Data extracted from Annex 1, Table 19)

PV Module Type	Climate Change (kg CO_2 eq)	Water Use (m^3)	Resource Use, Fossils (MJ)	Resource Use, Minerals & Metals (kg Sb eq)
Standard (opaque)	0.029	0.027	0.335	3.40E-06
Semi-transparent (60%)	0.022	0.018	0.252	2.74E-06

1.8.2 INTERPREATION AND CONCLUSION

The results confirm that semi-transparent PV modules can provide meaningful environmental benefits compared to standard opaque modules, particularly when light-sharing with crops is a relevant design goal. While they offer lower impacts per kWh generated, their lower energy output per unit area should be carefully balanced with agronomic benefits and land availability.

From an eco-design perspective, both module types are valid options within the SYMBIOSYST system. The selection between them should consider not only environmental impact but also crop compatibility, system layout, and energy targets.

These findings complement the analysis of the mounting structure configurations and contribute to a holistic understanding of the environmental trade-offs within agri-PV system design.

1.9 ROBOT

This section presents the Life Cycle Assessment (LCA) of the robotic monitoring system developed within SYMBIOSYST. The analysis has been carried out according to the methodology defined by ISO 14040/14044, applying the EF 3.0 method as used throughout the LCA activities in WP4, and is fully documented in Annex 3 of this deliverable.

The scope of this LCA includes the autonomous robotic system designed for real-time environmental and crop monitoring in agri-PV installations. The system is intended to replace conventional fixed sensor networks (mesh of sensors), providing enhanced flexibility and efficiency. The analysis considers the entire cradle-to-grave life cycle of the robot, with the aim of informing eco-design decisions and contributing to the overall sustainability evaluation of the SYMBIOSYST agri-PV system.

A specific focus of this analysis has been the comparison between the robotic system and a mesh of fixed sensors, providing a quantitative basis to evaluate the relative environmental performance of the two monitoring approaches. The comparative assessment has been conducted based on a common functional unit of "monitoring 900 m² of agri-PV field over 10 years", ensuring consistency in the analysis.

The assumed lifetime of the robotic monitoring system is 10 years, consistent with the functional unit defined for the analysis (monitoring of 900 m² over a 10-year period). This duration reflects a realistic service life for autonomous field robots in agricultural applications, considering mechanical wear, environmental exposure, and typical replacement cycles reported by manufacturers.

The model assumes that no intermediate replacement of the robot or its embedded sensors occurs during this period. All components are considered to be operational for the full duration. While this is a simplification, it reflects current design expectations and allows for a consistent comparison with the fixed-sensor mesh alternative, which is also modelled without replacements.

The following configurations have been assessed:

- Robot-based monitoring system (1 robot operating over 10 years)
- Mesh of sensors (18 sensor sets required to cover 900 m² for 10 years)

1.9.1 KEY RESULTS

The results of the LCA show that the robotic monitoring system offers substantial environmental advantages compared to a conventional mesh of sensors, particularly in terms of climate change impacts and resource use.

The robot achieves lower global warming potential (GWP), reduced fossil resource consumption, and lower water use, due to its lower material footprint per hectare and efficient operation.

As expected, land use and mineral/metal resource use are slightly lower for the mesh of sensors, given the smaller size of individual devices. However, the higher number of units required and the associated cumulative impacts lead to higher overall impacts in other categories.

The following table summarizes the key impact categories for the two monitoring approaches (values are per functional unit: 1 monitored hectare over 5 years):
Table 3.3.1 — Summary of main LCA impact indicators for the robotic monitoring system
(Data extracted from Annex 2)

Table 0.4. Summary of main LCA impact indicators for monitoring system configuration (Data extracted from Annex 3, Table 10)

Impact category	Unit	Robot (5 yrs / 1 ha)	Mesh of sensors (5 yrs / 1 ha)
Climate change	kg CO_2 eq	126.6	235.8
Resource use, minerals and metals	kg Sb eq	0.0046	0.0034

Resource use, fossils	MJ	1,883.5	3,578.2
Land use	Pt	9.01	5.21
Water use	m^3 depriv	0.47	0.94

To provide an overview of the main contribution to the environmental impact, in Figure 3.3 the contribution of the different lifecycle stages is visualized for all the impact categories, for the mesh of sensors case, showing that the operation is most often the most relevant category, except for the resource use, minerals and metals, where the manufacturing has the highest contribution.

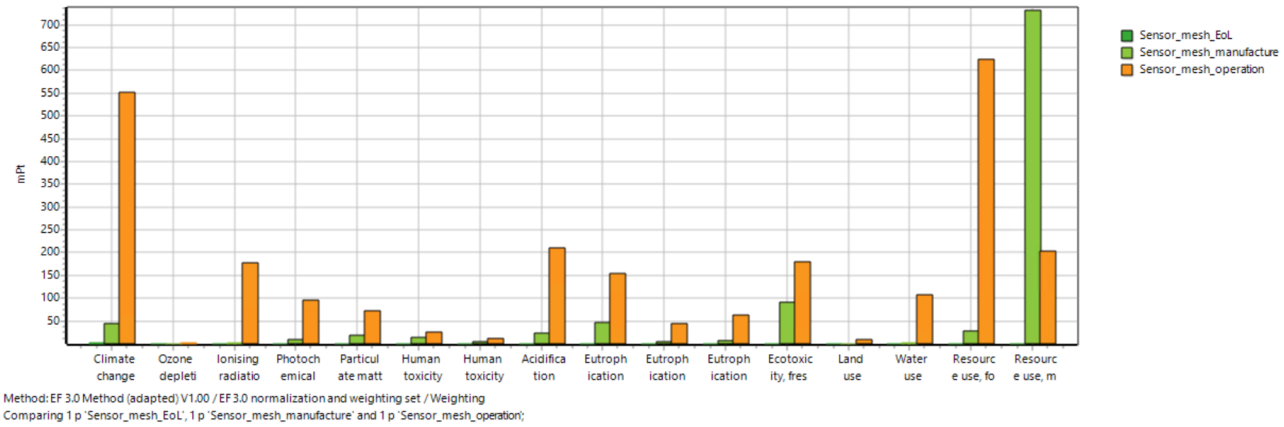


Figure 0.3. Summary of main LCA impact indicators for monitoring system configurations (Data extracted from Annex 2, Table 10)

1.9.2 INTERPREATION AND CONCLUSION

The results confirm that the robotic monitoring system represents a promising solution from an environmental perspective, offering clear advantages over the mesh of sensors in terms of climate change impacts, resource use, and operational flexibility.

The reduced material demand and the ability to cover larger areas with fewer devices contribute to the superior environmental performance of the robot-based approach. These findings provide valuable input for the ongoing design optimisation of monitoring solutions within SYMBIOSYST and for the broader adoption of such systems in future agri-PV applications.

CONCLUSIONS

This deliverable has presented the outcomes of Task 4.2, complemented by the results of those Task 4.1 activities originally planned for D4.1, with the objective of providing a comprehensive sustainability and eco-design assessment of the SYMBIOSYST technologies.

In Section 2, the design activities carried out under Task 4.1 have focused on the definition of low-impact materials and optimised configurations for PV modules and mounting structures. The work has explored the potential of EU-made low-carbon PV cells, optimised frame designs, and alternative backsheets, supported by reliability testing and sensitivity analysis.

Key eco-design conclusions from Task 4.1 highlight several opportunities to reduce environmental impacts while maintaining technical performance. The use of semi-transparent PV modules, with reduced silicon content, has been shown to significantly lower impacts in categories such as climate change and resource use, without compromising crop compatibility. Similarly, replacing aluminium with steel in frame structures can reduce the embedded burden in mineral and metal resource categories while ensuring structural stability. The adoption of fluorine-free backsheets offers further environmental gains with no loss of durability. Finally, optimising frame dimensions and material thickness allows for measurable reductions in material demand and embodied energy, contributing to a more efficient system design.

These results provide important guidelines for the eco-design of agri-PV systems.

In Section 3, the Life Cycle Assessment of key SYMBIOSYST technologies has been presented, providing quantitative results to inform design decisions and support circularity optimisation. The analysis included:
The mounting structures + PV modules, with a detailed comparative assessment of wood vs steel structures developed in collaboration with Task 3.1. These results have directly supported the decision-making process for Milestone MS4, providing an evidence-based evaluation of the feasibility and sustainability potential of wood-based solutions. The analysis shows that wood-based structures, when combined with adequate maintenance strategies (e.g. coating or replacement), can achieve significantly lower impacts in climate change and fossil resource use categories, while the steel reuse scenario also offers substantial benefits. Regarding the PV modules, the analysis confirms that semi-transparent modules (with ~60% cell coverage) result in consistently lower environmental impacts compared to standard opaque modules, particularly in climate change, water use, and resource depletion indicators. This is mainly due to reduced material intensity, especially silicon and aluminium. These findings support the selection of light-transmitting PV technologies as a viable eco-design option in agri-PV systems where crop productivity and sustainability must be balanced.

The robotic monitoring system, evaluated as an alternative to a conventional mesh of fixed sensors. The results demonstrate the potential of the robotic approach to achieve lower environmental impacts while enhancing operational flexibility and scalability. The robot consolidates material use into a single mobile unit and reduces long-term energy demand, whereas the fixed-sensor mesh shows higher impacts due to continuous electricity use and distributed electronics across the field.

Overall, the analyses confirm that eco-design choices — including material selection, lifetime optimisation, and design of monitoring solutions — can significantly influence the environmental performance and resource circularity of agri-PV systems. The work presented here provides concrete guidance for ongoing design refinement within the project.

Although the digital services component has not been included at this stage, future LCA updates will incorporate this aspect as the platform matures, completing the overall sustainability assessment of the SYMBIOSYST system.

It should be highlighted that the methodology, modelling framework, and results developed in this deliverable will serve as the fundamental basis for the Life Cycle Assessment of the SYMBIOSYST pilot installations, to be conducted under Task 4.4. These assessments will be applied to the systems implemented in the SYMBIOSYST demo cases in WP5, ensuring methodological consistency between the design phase (WP4) and the real-world deployment phase (WP5). The work presented in D4.2 thus provides a robust foundation for the integration of eco-design and circularity principles into the demonstration phase and supports the broader replication potential of the SYMBIOSYST approach.

ANNEX 1: LCA OF MOUNTING STRUCTURES AND PV PANELS

The Life Cycle Assessment, or LCA, is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.
The process of performing an LCA analysis is standardized in two main ISO standards, recognized at the international level as the reference documents for this type of assessment: the ISO standard 14040:2006/2020 (Environmental management, Life cycle assessment, Principles and framework), that frames a common methodology to be followed when performing an LCA analysis, and the ISO standard 14044:2006/2020 (Environmental management - Life cycle assessment - Requirements and guidelines), that complements it by describing in more detail such approach, also defining specific requirements.
The standards identify 4 main phases that compose the LCA approach:

- **Goal and scope definition:** this preliminary phase is crucial to define the goal of the study performed, and to clarify the boundaries, requirements and assumptions introduced to achieve such goals.
- **Inventory analysis:** this phase encompasses the quantification of all the input and output fluxes that compose the system under assessment, throughout all its lifecycle, as well as their modelling.
- **Impact assessment:** in this phase, the quantification of the impacts of the system under consideration on different environmental indicators is performed.
- **Interpretation of the results:** this phase combines the previous ones, in order to analyze the results coherently with the methodological choices made. This is an iterative process allowing to identify potential aspects to be improved in the model, and to develop interpretations, conclusions and recommendations.

The present study is performed in accordance with the guidelines indicated in the mentioned ISO standards, and the present report is structured accordingly.

1.1 GOAL AND SCOPE

1.1.1 GOAL

The goal of the present study is to perform an LCA study to assess the environmental performance of the agrivoltaics system under evaluation within the SYMBIOSYST project, with the configuration applied in the UPC use case (Agrivoltopolis).

The plant assessed, that will also be called the SYMBIOSYST configuration, will be installed in Baix Llobregat, in the Barcelona province and is made of 10 PV trackers, for a total of around 47m x 19.2m (approximately 900 m^2). The total installed power in this field is 48 kWp.

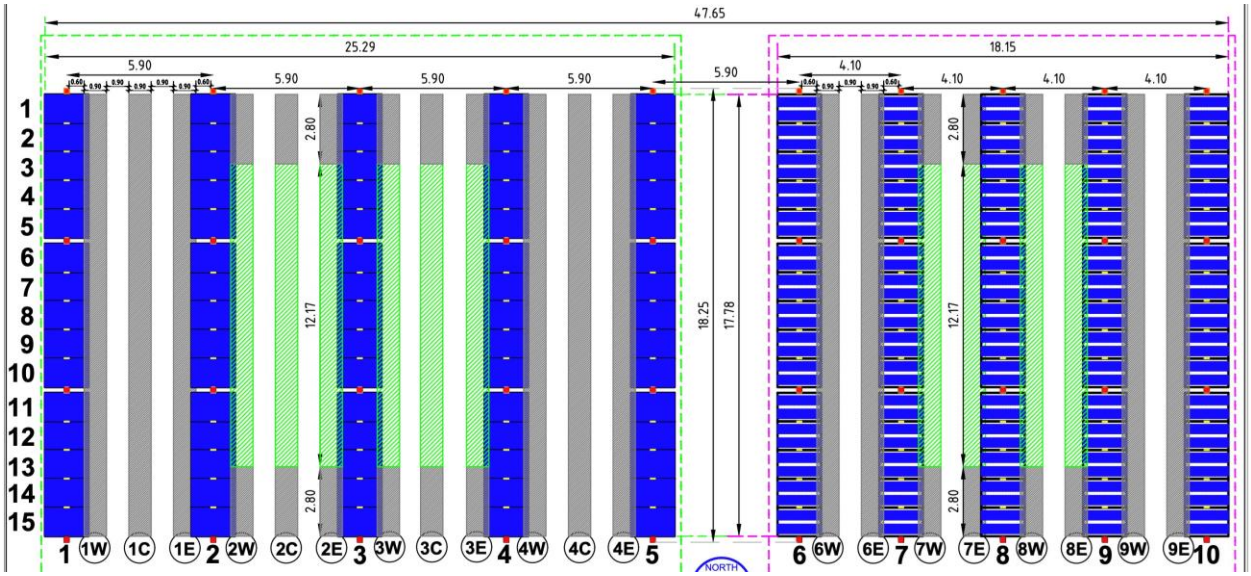


Figure 1.1. SYMBIOSYST configuration

In parallel, the assessment is also performed on the same plant applied on a total surface of 1 hectare; in this case, different scenarios for the PV type and tracker distances are analyzed, as it is thoroughly described in section 1.3.1 and 1.3.2.

The aim is to evaluate the impact of the elements composing the system on the different impact categories selected, and their combination in the different configurations.

In addition, the hectare configurations will be compared with the base case in which the same amount of electricity generated by the plant is, instead, purchased by the national grid (Spanish data).

The analysis will be performed using the software SimaPro, that allows to model the system analyzed and to evaluate the corresponding impacts on the categories selected. More information on the modelling choices is provided in section 1.3, and on the software version, methods and database used.

1.1.2 SCOPE

1.1.2.1 *SYSTEM ELEMENTS*

The present study includes three elements of the agrivoltaics system: the PV structure and tracker, the photovoltaic system and the crops. The details of their composition and schemes describing their structure are presented in section 3 (inventory analysis). The system scheme, and the three main elements considered in the present document, are depicted in the following figure.

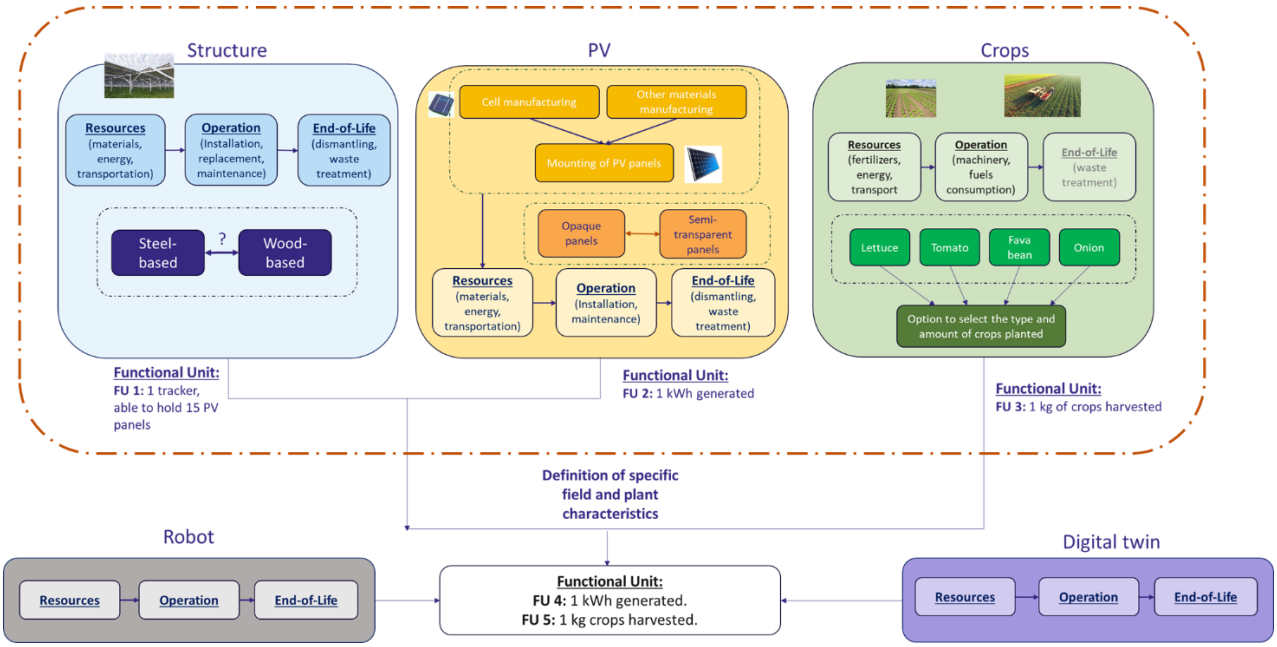


Figure 1.2. System scheme

For the PV structure, different scenarios are evaluated: the base case, in which the structure is mainly composed of steel elements, and an alternative one in which some of the steel components (poles and beams) are replaced by wood elements.

For what concerns steel, the base case foresees that the steel elements are specifically used for this application and will be sent to recycling after the use (30-years lifetime). Another sub-scenario takes into account the fact that steel has a longer lifetime than the agrivoltaics plant one, namely 60 years. Therefore, it is assumed that the elements will be successively used for further applications (for example, for another agrivoltaics plant), and therefore only a part of their impact, around 50% of the total, is to be allocated to the present plant.

Regarding wood three different sub-cases are evaluated: the case in which the wood elements resist throughout the whole lifetime of the system (30 years) and two more conservative cases. In one scenario, after 15 years the wood elements have to be replaced because of strength reasons. In fact, the manufacturers guarantee the durability of the wood poles only for the first 15 years; nevertheless, although not guaranteed, it is highly likely that the wood elements resist more than this period. In other one the wood is not replaced, but is expected to be covered with a protective paint coat in order to ensure higher durability of resource. The coat is applied every 7-8 years, for a total of 4 times throughout the lifetime.

With regards to the crops, the project assesses scenarios in which 4 different plants are grown: tomatoes, onions, fava beans and lettuce. For each of them, the evaluation is performed separately.
Summarizing, the systems analyzed are the following:

1. PV structure.
    a. Steel Scenario (base case, 30 years)
    b. Steel scenario (60 years, re-use)
    c. Wood scenario (30 years, no replacement)
    d. Wood scenario 15 years (replacement)

    e. Wood scenario, with coating (no replacement)
2. PV panels.
    a. Base opaque PV
    b. 60% opaque PV
3. Crops.
    a. Tomatoes
    b. Onions
    c. Fava beans
    d. Lettuce

The plant is not implemented yet; therefore, the analysis is performed ex-ante, and is not based on data collected after the implementation. The plant considered is the Use Case "Agrivoltopolis" of the SYMBIOSYST project, a configuration with 10 trackers. The plant is going to be implemented in Baix Llobregat, in the Barcelona province.

Two different specific configurations will be considered in this analysis, defined for the use case study configuration and for the same configuration applied on a total surface of 1 hectare (as it will be thoroughly explained later on). Lastly, the impacts of the electricity generated through these plants will be compared with the ones referred to electricity from the national energy mix in Spain.

1.1.2.2 *FUNCTIONAL UNIT*

The functional unit is the base unit for which the results of the analysis are provided. It has to be as simple as possible, in order to represent the system's goal and scope and to allow for consistent comparisons. In general, the unit is defined according to the characteristics of the system analyzed. Because of this, each part of the system is analyzed considering a different unit. Successively, the units will be converted to a common one, and will be combined in order to achieve a global analysis.

For what concerns the PV structure, the functional unit (FU1) is 1 tracker, able to hold 15 PV panels (in the specific case, "leo 400-415W") for a total installed power of 6 kWp.

1 kWh of electricity generated has been used as the functional unit of the PV plant (FU2).

1 kg of crops output will be used as functional unit 3 (FU3) for the systematic comparison of the harvesting part.

The period of operation is 30 years.

The global evaluation of the whole plant has been realized considering both the structure and the PV panels. In this case, the functional unit is 1 kWh generated by the plant (FU4). In addition, later on in the project the whole plant function will also be evaluated with the FU5, namely 1 kg of crops.

1.1.2.3 *SYSTEM BOUNDARIES*

The definition of the system boundaries is crucial to determine the processes, materials and energy fluxes to be included in the analysis.

The final study system boundary is cradle-to grave. This means that the assessment encompasses all stages from the extraction of the materials used (cradle) to the treatment of the waste generated at the end of the lifecycle (grave).

The technology system lifecycle is thus evaluated along the main three processes: Upstream (everything related with the processes that occur before the technology is installed), Core (all the aspects directly related with the operation of the system) and Downstream (all the processes that occur after the lifecycle ends).
In general, the lifecycle stages and the main sub-stages that will impact the results are the following:

UPSTREAM

- Extraction,
- Transportation,
- Processing of raw materials.

CORE

- Energy consumptions during operation,
- Re-painting of wood elements with protective coating,
- Replacement of elements during the lifetime.

DOWNSTREAM

- Waste transportation,
- Waste treatment.

Some additional stages have been excluded from the scope of the study. For example, the auxiliary materials used during the production processes, or the water consumptions, waste generation during the production processes etc. These stages are not included since they are considered to be negligible if compared to the other stages; in addition, direct data are only available for the steel scenario of the PV structure. Comparing results obtained from data with different levels of precision could hinder the results obtained, giving a higher impact weight to the scenario with more details. Because of these, it was decided not to do it, and to exclude these minor data from the study.

1.1.2.4 *TIME AND GEOGRAPHICAL DATA REFERENCE*

The datasets used in the modelling are selected to be as representative as possible of reality. The geographic coverage of data is as follows:

- Spanish data for electricity. This refers to all the cases in which the consumption is directly from the grid, for example during the assembly/disassembly phases, since the installation is expected to be located in Baix Llobregat, in the Barcelona province.

- European data for materials processing and manufacturing processes (for example the production of metal components or the transportation means).

- European or global data for raw materials usage.

These choices depend on the availability of specific datasets. In terms of timeframe, the data used are estimations and data collected in late 2023/2024.

1.1.2.5 *DATA QUALITY*

The specific data used for the modelling of each component and the corresponding explanations are detailed in section 3 (inventory analysis).

For a general overview, for what concerns the PV panels the data used in the present assessment are estimations according to literature, building on the information available on the PV panels selected. The tracker structure data are provided by the suppliers (Convert); some data, especially the ones related to the wood components, are obtained from estimation of the elements size and by wood poles producers information. Regarding the crops, the data are provided by the university department that focuses on this topic, and represent estimations defined beforehand, and will be confirmed by the project testing.
In all cases, the data used can be categorized as "selected secondary data", meaning they are modelled through internationally recognized datasets with confirmed direct correlation between the dataset and the actual flux. These datasets preserve the correlation between the model and the actual processes, accurately representing them in terms of geography and time period.

In this study, all the selected datasets are from the Ecoinvent 3.6 database.

1.1.2.6 *USE STAGE ASSUMPTIONS*

The use phase is included in the model. Nevertheless, the operation of this system is not expected to involve noticeable consumptions.

For what concerns the PV plant, no operation consumptions are considered. The regular maintenance does not involve specific energy or material consumptions; therefore, no use stage impacts are expected (in addition, this stage would be similar in the case of the 2 scenarios assessed, thus,the results would not significantly differ in a comparative perspective). The replacement of some of the components (such as the inverter, panels that undergo problems) is included in the upstream stage.

With regards to the PV tracker structure, similar assumptions can be made. No operation activities are expected to occur in the steel scenario. In the wood scenarios the operation stage varies according to the scenarios. In the base case, where the wood elements are not painted or replaced, no operation is expected. In the scenario with the replacement of wood components, the model encompasses in the use stage the materials extraction, processing and the waste disposal for the new wood components, as well as the processes of installation (especially, the use of machinery for the works). In the scenario where the paint coating is expected, the operation stage encompasses the process for which all the wood elements are assumed to be re-painted every 7-8 years.

1.1.2.7 *WASTE TREATMENT APPROACH*

In order to evaluate the impact of the End-Of-Life stage some assumptions on the waste scenario have to be introduced. Regarding recycling, the Polluter-Pays Principle (PPP) was used, according to the recommendations of the General Programme Instructions developed by the International EPD® System . According to this, the impact of the recycling process for the materials sent to recycling is attributed to the following lifecycle. Therefore, in this case, only the transportation of the materials to the treatment site is considered.

1.2 INVENTORY ANALYSIS

To simulate the described scenarios, each component comprised in the configurations was modelled. This chapter presents the modelling decisions undertaken, and presents the datasets used to characterize each

element. In some cases, technical information is reported, for example the complete names of the datasets selected form the database, or aspects related to the structure of the modelling in the SimaPro software; this is made in order to provide experts with all the specific modelling details; in any case, the specific understanding of all these details is not necessary for the overall comprehension of the analysis performed.

1.3 PV TRACKER STRUCTURE

The PV structure is modelled according to the information directly provided by the supplier partner.

The structure includes 4 poles for each tracker, beams to hold the PV panels and some other structural elements needed for the optimal operation of the plant, as summarized in the following schemes. In Figure 1.3 the scheme for the steel structure is presented, while in Figure 1.4 the wood structure one.

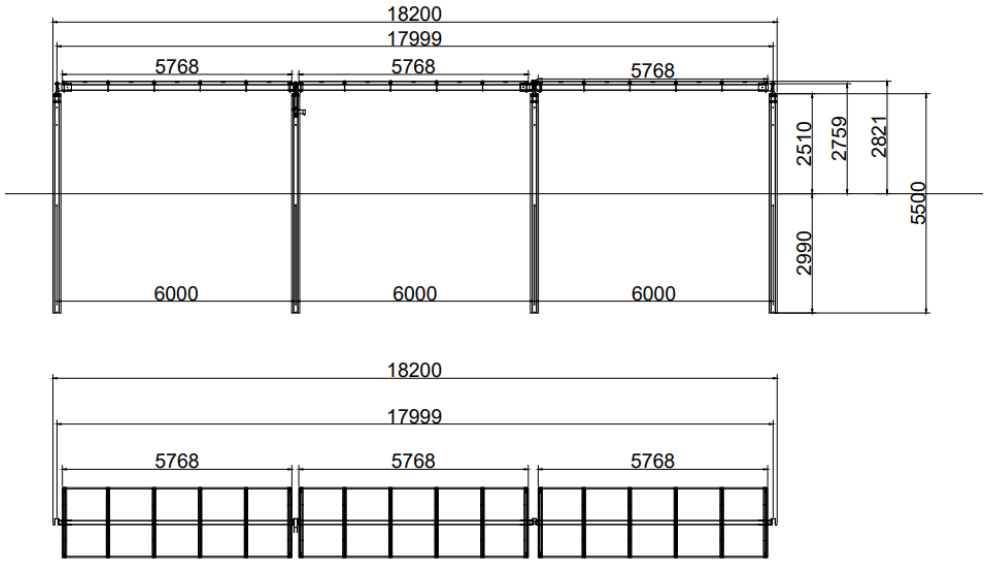
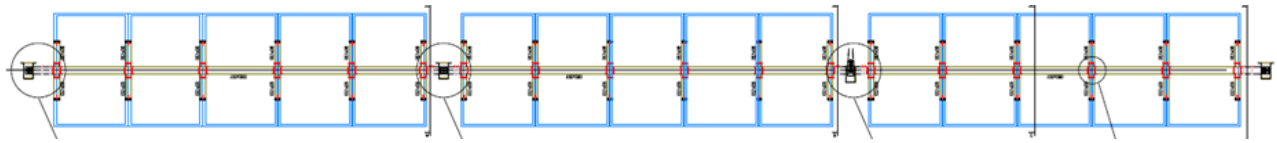


Figure 1.3. Tracker scheme, steel structure



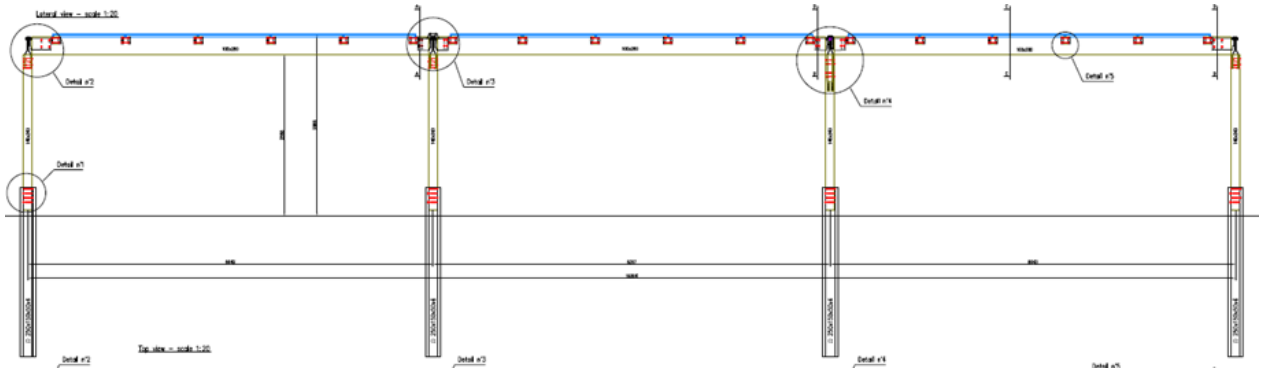


Figure 1.4. Tracker scheme, wood structure

Hereafter, all the modelling choices made to describe the structure are listed. The data are identified according to the specific scenario.

1.3.1.1 *STEEL SCENARIO*

In this case, the data used is indicated by the suppliers (Convert).

In order to describe the modelling made in the software, a list of materials and processes used is provided in Table 1. The table reports the dataset selected to model each material that composes the system. The second column reports the name of the datasets used, as they are named in the database and as available in the software, in order to allow easy tracking of the modelling made. When the datasets indicate the acronym "RER" it means they refer to average values for Europe, while "RoW" refers to the rest of the world. When they are country-specific, such as for the electricity, they indicate the country (in this case, "ES" for Spain). These basic datasets are later combined to build the actual components model.

Table 1.1. List of simple datasets used in the model

Dataset in SimaPro	**Material/process in Ecoinvent 3**
Aluminium ingot	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | Cut-off, S
Aluminium recycled	Aluminium, cast alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner | Cut-off, S
Stainless steel converter	Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8 | Cut-off, S
Stainless steel electric	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, S
Steel converter	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, S
Steel electric	Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Cut-off, S
Aluminium cast process	Casting, aluminium, lost-wax {RoW}| casting, aluminium, lost-wax | Cut-off, S

Dataset in SimaPro	Material/process in Ecoinvent 3
Extrusion Aluminium Process	Section bar extrusion, aluminium {RER}| processing | Cut-off, S
Extrusion steel process	Impact extrusion of steel, hot, 3 strokes {RER}| processing | Cut-off, S
--> the 3 strokes one is selected, since it is the average, and the info is not available	
Stainless steel manufacturing Process	Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S
Steel average manufacturing Process	Metal working, average for steel product manufacturing {RER}| processing | Cut-off, S
Zinc coat process	Zinc coat, pieces {RER}| zinc coating, pieces | Cut-off, S
Lorry 16-32 t	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S
Lorry, 7,5-16 t	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, S
Medium car diesel	Transport, passenger car, medium size, diesel, EURO 5 {RER}| transport, passenger car, medium size, diesel, EURO 5 | Cut-off, S

The data presented later on refer to the whole system, namely the 10 trackers used for the selected configuration of the SYMBIOSYST project. Successively, the impact obtained for the whole structure will be allocated to the functional unit that, as specified, is 1 tracker.

Structure

The structure components can be split into three main groups:

- Steel structure tracker
- Steel structure assembly
- Steel structure transportation

The tracker dataset, as envisioned in the project, foresees the presence of 10 trackers, 1 assembly and the transportation of the components (1 dataset as defined later).

Hereafter, the modelling choices made are presented.

Steel tracker structure

The components of the structure of 1 tracker are modelled as follows. As mentioned before, the model of the total structure considers 10 datasets of the steel structure tracker, since 10 trackers are expected to be installed in the plant; therefore, the data presents are to be multiplied by 10 to obtain all the material of the total configuration (10 trackers). The total weight of 1 structure is 799.3 kg, for a total of 7’993 kg for the whole configuration.

The table reports the name used in the software to describe each component, as well as the type and weight of materials that compose each of them. In addition, the modelling of each component considers that the materials are modified through manufacturing processes in order to obtain the products; the manufacturing processes considered in the model for each component are reported in the "process used" column of the table. The materials and processes listed in the table below are described previously in Table 1.

Table 1.2. Datasets used for 1 tracker structure, steel scenario

Components: Dataset created	Material used	Process used
Alu tube D50	Alu ingot (0.48 kg)	Extrusion Aluminium Process (0.48 kg)
Aluminium die casting	Alu recycled (0.776 kg) Alu ingot (0.068 kg)	Aluminium cast process (0.844)
Extruded Alu frame stator	Alu ingot (0.207 kg)	Extrusion Aluminium Process (0.207 kg)
Foundations	Steel converter (118.46 kg) Steel electric (375.13 kg)	Zinc coat process (24.68 kg)
Magnetic steel	Stainless steel conv. (0.21 kg) Stainless steel el. (0.745 kg)	Stainless steel manufacturing Process (0.955 kg)
Screw bar	Steel electric (0.661 kg)	Extrusion steel process (0.661 kg)
Stainless steel rod	Stainless steel conv. (0.22 kg) Stainless steel el. (0.44 kg)	Stainless steel manufacturing Process (0.665 kg)
Steel hub	Steel conv. (0.0012 kg) Steel el. (0.06 kg)	Steel average manufacturing Process (0.061 kg)
Steel motor shaft	Steel conv. (0.141 kg) Steel el. (0.139 kg)	Steel average manufacturing Process (0.28 kg)
Specific steel	Pre-galvanized steel module tubes and supports (1 unit) Kit components (1 unit)	-

Where the two specific datasets are defined as follows:

Kit components	Steel conv. (11.96 kg) Steel el. (37.89 kg)	Zinc coat process (2.49 kg)
Pre-galvanized steel module tubes and supports	Steel conv. (53.89 kg) Steel el. (170.67 kg)	Zinc coat process (11.23 kg)

Steel structure assembly

The specific datasets used to model the assembly process, as well as the assumptions introduced, are reported in the Table 3. In this case, the data refers to the whole system (10 trackers).

Table 1.3. Datasets used for the structure assembly, steel scenario

Dataset created	Dataset in Ecoinvent 3	Details
Assembly phase	Diesel, burned in building machine {GLO}| market for | Cut-off, U	181.4 MJ It includes: components transport in the field, and the installation through machinery
	Electricity, low voltage {ES}| market for | Cut-off, U	11 kWh It includes: mounting

Steel structure transportation

The dataset used to model the transportation of the structure elements to the plant site, as well as the assumptions introduced, are reported in Table 4. The total weight transported is 799.3 kg for each tracker, for a total of 7'993 kg. In this case, the data refer to the whole system (10 trackers).

Table 1.4. Datasets used for the structure assembly, steel scenario

Dataset created	Dataset in Ecoinvent 3	Details
Steel structure transportation	Lorry 16-32 t	Steel transportation: 1000 km assumed. Total weight 7'993 kg.

1.3.1.2 *OPERATION*

As mentioned before, the operation part is not included in this study, since no maintenance actions are expected to occur during the considered period, and no direct consumptions are needed.

1.3.1.3 *END-OF-LIFE*

The End-of-Life (EoL) stage for the PV tracker structure is modelled with a specific functionality available in the SimaPro software. This functionality allows to automatically evaluate the impacts of the End-of-Life stage, without having to select each specific treatment dataset. On the other hand, a disposal scenario for the system under consideration has to be defined in the model. In this case, it was considered that around 98% of the total components and materials are correctly disassembled (assuming a 2% of materials losses during the lifetime, that are partially incinerated and partially landfilled). The dismantling takes place by separating all the sub-assemblies, that are successively transported to the treatment places. For each component of the structure, it is assumed that 95% of the base materials that compose it can be recovered, with around 5% of material losses (that are sent to waste treatment, modelled as an average treatment mix). The recovered materials are mainly reused, and partially disposed in landfills. The percentage varies according to the specific component considered; in any case, the reuse rate is estimated to be high, between 75% and 90%. The structure of the disposal scenario described is summarized in Figure 5.

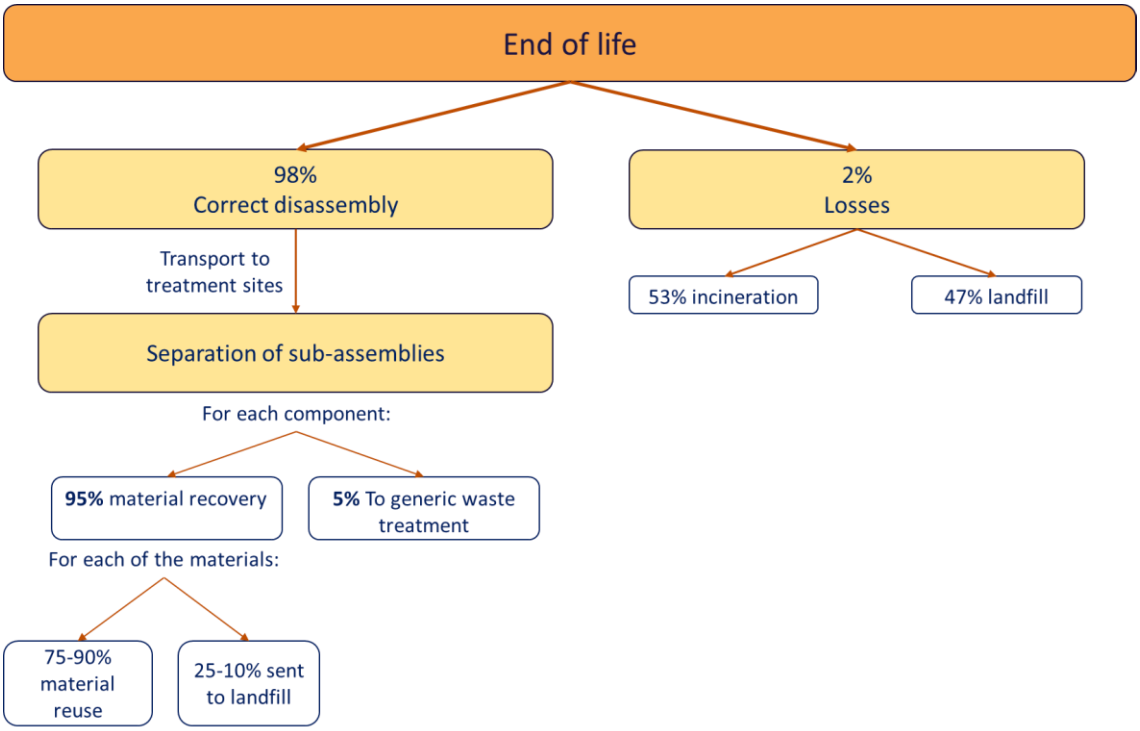


Figure 1.5. End-of-life modelling scheme

The details of the specific values modelled are presented in the following table: the reported data is technical and is reported through the nomenclature and the scenario structure needed by the software, in order to allow for a correspondence check in case of specific needs. End-of-Life is shortened in the table as "EOL".

Table 1.5. Disposal scenario, steel scenario

Components: Dataset created	**Material used**
EOL: disposal scenario of the whole structure We assume that there is 2% loss in the disposal of the structure due to the lifetime.	Losses: 2% Correct disassembly: 98%
EOL: Disassembly of the whole structure	Separation of sub-assemblies: Disposal tracker steel: 100% Waste scenario: 100% in France (closest option)
EOL: Disposal of tracker Assumption: there is no loss in the disposal of the tracker, all the losses are counted in the disposal of the structure.	Waste: 0% Disassembly: 100%
EOL: Disassembly of tracker	1 dismantling part waste treatment 50 km away the site Transport by lorry 7.5-16 t, EURO6

Components: Dataset created	Material used
Assumption: there is 5% loss in the disassembly of the tracker for each sub component.	Separation of sub-assemblies: Disposal steel shaft motor: 95% Disposal steel hub: 95% Disposal stainless steel rod: 95% Disposal screw bar: 95% Disposal specific steel: 95% Disposal magnetic steel: 95% Disposal foundations: 95% Disposal extruded alu frame stator: 95% Disposal alu die casting: 95% Disposal alu tube D50: 95% Waste scenario: 100% in France (closest option)
EOL: Disposal scenario of each sub component (%waste/%recycled) In each case, we assume that there is 5% loss	alu die casting: 10/90 extruded alu frame stator: 10/90 steel shaft motor: 20/80 steel hub: 10/90 stainless steel rod: 20/80 screw bar: 10/90 magnetic steel: 20/80 foundations: 25/75 alu tube D50: 10/90 specific steel: 10/90

Additional processes, namely the dismantling operation and the transportation of waste to the treatment plant, are included in the analysis, as shown in the following table.

Table 1.6. Disassembly other processes, steel scenario

Dataset created	Processing in Ecoinvent 3	Details
Dismantling tracker steel	Diesel, burned in building machine {GLO}| market for | Cut-off, U	124.5 MJ It includes the extraction of poles and dismantling operations
	Electricity, low voltage {ES}| market for | Cut-off, S	12.6 kWh It includes dismantling operations
Transportation to the waste treatment plant	Lorry, 7,5-16 t	400 tkm 50 km distance between the site and the treatment plant

Regarding the End-of-Life treatment, the assumptions made were based on statistics available in the future, listed later on, and to considerations due to the future potential evolution of these trends.

For aluminium and steel recycling the statistics provided by ADEME (DEVAUZE C., KOITE A., CHRETIEN A. et MONIER V.), "Bilan National du Recyclage 2010- 2019 - Évolutions du recyclage en France de différents matériaux: métaux ferreux et non ferreux, papiers-cartons, verre, plastiques, inertes du BTP et bois." – (2021). According to the reports published by EuRIC, 90 % of the aluminium in construction and transportation is reused. According to the report published by the French national institute for the circular economy about the steel, 80 % of stainless steel is recycled and near 100 % of steel from construction is recycled, we consider that 95% is recycled at the end.

According to Galvazinc, an independent French association of experts in hot-dip galvanising, 68% of zinc is recovered after the galvanised steel separation process.

In the steel recycling section, we consider the creation of new, second-hand steel parts. To do this, we consider the process of melting, refining, adjusting the composition if necessary, casting and forming. During these transformations, zinc does not have the same melting point as steel, so it is relatively simple to separate them. That's why we won't be adding any additional processes to separate these 2 components.

1.3.1.4 *Steel scenario, 60 years*

A second scenario has been introduced with regard to the steel structure case. In fact, steel is a resistant and long-life material that can operate for more than the 30 years analyzed in this system lifetime. Because of this, the steel scenario could neglect some of the advantages introduced by this material by limiting the time span taken into account.

In order to have a look at this aspect, another steel scenario is introduced. It is considered that, after the system lifetime of 30 years, the steel poles and beams are re-used for new similar structures. Considering a total lifetime of the steel components of 60 years (conservatively), the impacts of these components can be partially allocated to the present system and partially to the future ones. Therefore, only 50% of their impact is considered in the present analysis. The elements for which this assumption is made are the poles (Foundations dataset in Table 1.2) and the beams (Pre-galvanized steel module tubes and supports, and kit components datasets in Table 1.2). As a consequence, also the end-of-life treatment of these elements will be scaled with the same coefficient of 50%. It should be noted that the total weight of the system elements is the same as for the steel scenario.

All the other data and assumptions are the same presented in the steel scenario.

1.3.1.5 *WOOD SCENARIO*

The second scenario analyzed is the one in which some of the steel components are replaced by wood. Also in this case, three main areas can be identified.

Structure

Compared to the steel structure, the elements that are replaced are part of the beams that hold the PV panels and of the foundations poles that hold the whole structure. The parts that are replaced by wood are the ones depicted in green in Figure 1.4.

Translated in the specific datasets modelled, as presented in the previous sections, the components that vary from the steel case are two:

- The “Pre-galvanized steel module tubes and supports” (part of the “Specific steel” dataset). In this case, the beams are replaced with wood. As can be observed in the figure, 3 long transversal beams are considered, as well as 18 shorter ones. The total weight of these wood elements is 338.1 kg for each tracker (with a volume of 0.615 m^3).

- Part of the “Foundations”. In this case, only a portion of this material is supposed to be replaced, since the part in contact with the ground is kept as in the base case, namely in steel. Therefore, 50% of the steel is assumed to be replaced by wood, while the galvanization process, that was only performed to the lower part of the foundations, remains. In this case, each tracker has 4 wood poles, with a total wood weight of 181.5 kg (0.33 m^3).

The modelling of the wood has been done considering that a resistant wood is needed; therefore, a glulam wood type has been selected (glued laminated timber). The dataset selected in the database for this type of wood already includes the transportation from the forest to the processing site, and all the processing that the wood undergoes. In addition, the wood has to undergo an autoclave treatment in order to be able to resist throughout the period.

The values used in this scenario, instead of the “Specific steel” and of the “Foundations” datasets, are presented in Table 1.7. The total weight of 1 tracker is, in this case, 847.6 kg, for a total of 8’476 kg for the 10 trackers.

As done for the steel scenarios, the tracker materials data presented refer to 1 tracker, and have to be multiplied by 10 to assess the total amounts of materials and treatments for the whole structure.

Table 1.7. Difference in the datasets used for the tracker structure, wood scenario

Components: Dataset created	**Material used**	**Process used**
Poles wood (For each tracker) (10 units, 1 for each tracker)	• Glulam wood (0.615 m3) Where the dataset in Ecoinvent is: “Glued laminated timber, for outdoor use {RER}| production | Cut-off, U”	Autoclave treatment (4.9 kg)
Foundations wood (For each tracker) (10 units, 1 for each tracker)	• Steel conv. (59.2 kg) • Steel el. (188 kg) Wood with autoclave (0.33 m3)	• Zinc coat process (24.68 kg)

In this case, the data used are assumed building on the indication of poles manufacturers, and according to the dimensions provided by the tracker structure providers.

The remaining datasets are the same as in the steel scenario.

For what concerns the assembly stage, the same consumptions are assumed to be needed to assemble the wood structure.

In the case of transportation, the same assumptions made in the steel scenario are used (means of transport and distances). The only difference is the total transported weight, that as mentioned is a bit smaller. In fact, it is considered that the wood (5'196 kg) is supplied by more local suppliers, at 50 km distance, while the remaining 3'280 kg cover the initial distance of 1000 km.

Operation

In this base scenario, the operation stage is considered to be negligible. Since glulam wood is used, that is resistant and made for structural applications, this first scenario considers that no additional operations are made. In the following scenarios alternatives are proposed, in order to evaluate the case where these assumptions are not fulfilled.

End-of-life

The same logic and model structure presented in section 1.3.1.1 for the end-of-life modelling has been applied in this case (Figure 5). The table below reports the specific values introduced in the SimaPro software, according to the software modelling methodology. The same assumptions presented for the steel scenario are used for most of the elements involved.

The different assumptions introduced are presented in the following table.

Table 1.8. Disposal scenario, steel scenario

Components: Dataset created	**Material used**
EOL: disposal scenario of the whole structure We assume that there is 2% loss in the disposal of the structure due to the lifetime.	Losses: 2% Disassembly: 98%
EOL: Disassembly of the whole structure	Separation of sub-assemblies: Disposal tracker wood: 100% Waste scenario: 100% in France (closest option)
EOL: Disposal of tracker Assumption: there is no loss in the disposal of the tracker, all the losses are counted in the disposal of the structure.	Waste: 0% Disassembly: 100%
EOL: Disassembly of tracker Assumption: there is 5% loss in the disassembly of the tracker for each sub component.	1 dismantling part waste treatment 50 km away the site Transport by lorry 7.5-16 t, EURO6 Separation of sub-assemblies: Disposal steel shaft motor: 95% Disposal steel hub: 95%

Components: Dataset created	Material used
	Disposal stainless steel rod: 95% Disposal screw bar: 95% Disposal specific steel: 95% Disposal magnetic steel: 95% Disposal wood: 95% Disposal extruded alu frame stator: 95% Disposal alu die casting: 95% Disposal alu tube D50: 95% Waste scenario: 100% in France (closest option)
EOL: Disposal scenario of each sub component (%waste/%recycled) In each case, we assume that there is 5% loss	alu die casting: 10/90 extruded alu frame stator: 10/90 steel shaft motor: 20/80 steel hub: 10/90 stainless steel rod: 20/80 screw bar: 10/90 magnetic steel: 20/80 wood: 7.5/92.5 alu tube D50: 10/90 specific steel: 10/90

Additional processes, namely the dismantling operation and the transportation of waste to the treatment plant, are included in the analysis, as shown in the following table, and similarly to what happened in the steel scenario. In this case, the data refers to the whole system (10 trackers).

Table 1.9. Disassembly other processes, steel scenario

Dataset created	Processing in Ecoinvent 3	Details
Dismantling tracker steel	Diesel, burned in building machine {GLO}| market for | Cut-off, U	124.5 MJ
	Electricity, low voltage {ES}| market for | Cut-off, S	12.6 kWh
Transportation to the waste treatment plant	Lorry, 7,5-16 t	424 tkm 50 km distance between the site and the treatment plant

1.3.1.6 *WOOD SCENARIO, 15 YEARS REPLACEMENT*

Another scenario considered for the PV structure is the one in which the wood elements are replaced after 15 years of operation, as guaranteed by the poles' manufacturers. The total lifetime of the system is still considered to be 30 years.

From an operational point of view, these operations involve an important effort in terms of system re-configuration, including potential difficulties with the correct re-connection of all the elements. On the other hand, from an LCA perspective this scenario is very similar to the wood scenario, but is built to make it a bit more conservative.

For what concerns the structure and the end-of-life stages, there are no differences from the base wood scenario. The only differences can be observed in the operation part. This stage, that is added to the previously presented ones, is defined as in Table 1.10. The total weight of the wood part to be replaced is 519 kg for each tracker.

Also in this case, the data are reported for 1 tracker, and are to be multiplied by 10 to quantify the total materials involved.

Table 1.10. Datasets used for the structure assembly, steel scenario

Dataset created	Dataset in Ecoinvent 3	Details
Poles wood replacement (10 units, 1 for each tracker)	Glulam wood (0.33 m3) Where the dataset in Ecoinvent is: "Glued laminated timber, for outdoor use {RER}| production | Cut-off, U" Autoclave treatment (2.64 kg)	
Beams wood replacement (10 units, 1 for each tracker)	Glulam wood (0.615 m3) Autoclave treatment (4.92 kg)	
Wood replacement	Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, S Diesel, burned in building machine {GLO}| market for | Cut-off, U Electricity, low voltage {ES}| market for | Cut-off, S	260 tkm (50 km distance between the site and the manufacturing place) 306 MJ 23.6 kWh These values include the dismantling of the old parts and the installation of the new ones.
Disposal	Lorry, 7,5-16 t Waste wood, untreated {GLO}| treatment of waste wood, untreated,	260 tkm (50 km distance) 519.6 kg per each of the 10 trackers.

Dataset created	Dataset in Ecoinvent 3	Details
	open dump, moist infiltration class (300mm) | Cut-off, S	

1.3.1.7 *WOOD SCENARIO, WITH COATING*

The last scenario considered for the agri-PV structure, as well, takes into account the fact that the structure is located outdoor, and in an environment where the wood could be damaged (sun, chemicals, humidity, relatively close to the sea…). Instead of considering the replacement of the wood elements, another option is envisioned. The wood is expected to be protected from external agents through a coating paint layer. In this case, as in the previous scenario, the only stage that is modified from the base wood scenario is the operation one.

Operation

In this case, every 7-8 years the wood components are painted with a protective coating to ensure the proper conservation of these elements.
The dataset selected for this operation is “Alkyd paint, white, without solvent, in 60% solution state {RER}| market for alkyd paint, white, without solvent, in 60% solution state | Cut-off, U”. The total surface of wood to be painted, including all the elements described in the former sections, is 26.15 m2 per tracker. Considering 4 painting rounds in the 30 years, the total amount of painting needed is 13.6 kg per tracker, that means 136 kg of paint for the whole configuration.

1.3.2 PV PANELS

The other component analyzed in this part of the study is the PV panel system. In this case, a first scenario has been assessed, in which the PV panels used are the LEO 400-415 W Premium model (also called “standard PV”). A second sub-scenario is also assessed to complete the analysis (as will be presented when the results of the PV panels, structure and of the crops are combined). The second scenario is a variation of the base case, namely it will consider that the modules will only be made of 60% of cells while the remaining 40% will be made of translucent materials, allowing more solar radiation to reach the crops. These panels will be called semi-trans PV.

1.3.2.1 *STANDARD PV SCENARIO*

In this case, as mentioned, the LEO 400-415 W Premium PV panels are expected to be used. Data comes from literature review [1] and is thus not direct data from field collection.

As done in the previous section, the lifecycle stages can be split into three main steps.

Structure

The structure is made of 3 main elements: the panels, the inverter, and the panels transportation.

The panels are distributed in 10 trackers. For this reason, the data indicated for the PV panels are then multiplied by 10. The other stages are instead provided for the complete system.

The total weight of the PV panels is 706.9 kg for each tracker, that means a total weight of 7'068.5 kg for the 10 trackers.

For transportation, the total weight is a bit higher, namely 7'368.5 kg in total including the packaging.

Table 1.11 Structure, PV panels

Dataset created	Dataset in Ecoinvent 3	Details
PV PANELS (10 units of trackers). For each tracker:		
Electrical part tracker (1 unit for each tracker)	Electrical cable (93.5 m)	CN_Cable, connector for computer, without plugs {GLO}| production | Cut-off, U China electricity mix for the production of the cables used: Electricity, medium voltage {CN}| market group for | Cut-off, U
Modules (15 units for each tracker)	Cell - Cell monoSi 156x156 mm (108 units, 0.0166 m^2 each)	CN_Photovoltaic cell, multi-Si wafer {RoW}| production | Cut-off, U China electricity mix used.
	Glass flat uncoated (16.03 kg)	Flat glass, uncoated {RoW}| market for flat glass, uncoated | Cut-off, U
	Anti-reflective coating (2 m^2)	Anti-reflex-coating, etching, solar glass {RoW}| processing | Cut-off, U
	Ribbon cable Cu (0.378 kg)	Cable, ribbon cable, 20-pin, with plugs {GLO}| market for | Cut-off, U
	Electrical cable (2.4 m)	CN_Cable, connector for computer, without plugs {GLO}| production | Cut-off, U
	Plastic sheet (rear module) (2.56 kg)	Polycarbonate {RoW}| production | Cut-off, U Plastic sheet thermoforming: Extrusion of plastic sheets and thermoforming, inline {RoW}| processing | Cut-off, U
	EVA encapsulant (2.56 kg)	Ethylvinylacetate, foil {RoW}| production | Cut-off, U
	Aluminium frame (2.8 kg)	- Aluminium, primary, ingot {CN}| production | Cut-off, U - Metal working, average for aluminium product manufacturing {GLO}| market for | Cut-off, U

Dataset created	Dataset in Ecoinvent 3	Details
Inverter (1 unit)		
	Inverter (0.15 units)	Inverter, 500kW {RER}| production | Cut-off, U
Transportation (1 unit)		
	Train transportation	Transport, freight train {Europe without Switzerland}| electricity | Cut-off, U (1300 km, from Germany)
	Truck transportation (Lorry, 7.5-16 t)	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U (50 km from the manufacturing site to the train station, 50 km from the train station to the site)
	Packaging	Corrugated board box {RER}| market for corrugated board box | Cut-off, U

Operation

Along the lifetime of the plant, some operations are expected to be performed.

More specifically, the replacement of some modules is envisioned. The assumption is that 10% of the modules are replaced because of issues during operation before the end of the lifecycle. Similarly, the inverter is expected to be replaced once during the operation of the plant. The elements that are considered to be replaced are presented in the following table. The total weight of the new elements installed to the plant, namely the replaced components, is 58 kg for each tracker (580 kg in total). The transported weight, including the packaging, is 610 kg.

Table 1.12 Operation, PV panels

Dataset created	Dataset in Ecoinvent 3	Details
Module replacement (15 units). For each unit:		
Modules	Cell - Cell monoSi 156x156 mm (0.68 m^2)	CN_Photovoltaic cell, multi-Si wafer {RoW}| production | Cut-off, U
	Glass flat uncoated (16.03 kg)	Flat glass, uncoated {RoW}| market for flat glass, uncoated | Cut-off, U
	Anti-reflective coating (2 m^2)	Anti-reflex-coating, etching, solar glass {RoW}| processing | Cut-off, U

Dataset created	Dataset in Ecoinvent 3	Details
	Ribbon cable Cu (0.378 kg)	Cable, ribbon cable, 20-pin, with plugs {GLO}| market for | Cut-off, U
	Packaging corrugated boardbox (2 kg)	Corrugated board box {RER}| market for corrugated board box | Cut-off, U
	Aluminium frame (2.8 kg)	- Aluminium, primary, ingot {CN}| production | Cut-off, U - Metal working, average for aluminium product manufacturing {GLO}| market for | Cut-off, U
Transportation	Train (50 km away from the site)	Transport, freight train {Europe without Switzerland}| electricity | Cut-off, U
Inverter replacement (1 unit)		
	Inverter 500 kW (0.15 pieces)	Inverter, 500kW {RER}| production | Cut-off, U

End-of-life

For the PV panels, the End-of-Life stage has been modelled with a different approach than the one presented for the tracker structure (section 3.1.1). In this case, the End-of-Life of the product has been evaluated through the process's mode available in SimaPro. This methodological choice only means that the model structure in the software has been built with a different logic, but does not involve any concrete difference in the results or in the approach followed. In this case, the logic is simpler to follow and is based on the treatment type of each material that compose the PV elements, instead of focusing on each element one by one.

It is considered that components made of paper, glass and aluminium are sent to recycling. On the other side, cables and other electronic devices are expected to be properly disposed, and specific datasets are selected to consider the average rate of recycling and treatment of these materials. Finally, plastic elements are expected to be treated as follows:

- 45% recycling;
- 40% energy recovery;
- 15% disposal.

The datasets used in the model to describe the end-of-life of the PV system are reported in the following table.

List of simple datasets used in the model

Datasets	Datasets in Ecoinvent 3
Cables	Waste, electrical and electronic cables {GLO}| market for waste, electrical and electronic cables | Cut-off, U
Electronic devices	Used industrial electronic device {CH}| market for used industrial electronic device, WEEE collection | Cut-off, U
Plastic	Waste plastic, mixture {CH}| treatment of, sanitary landfill | Cut-off, U Waste plastic, mixture {CH}| treatment of, municipal incineration | Cut-off, U
Transport	Transport, freight, light commercial vehicle {RER}| market group for transport, freight, light commercial vehicle | Cut-off, U

1.3.2.2 *Semi-trans PV scenario*

This is a sub-case, in which there is a difference with the previous case. In fact, the modules are expected to be composed for around 60% of opaque cells (the common ones, as described before in the base case), while the remaining 40% is made by a translucent material that allows light to reach the crops.

The scenario is very similar to the previous one; the difference is only in the number of cells per module, that will be lower than the ones in the first case.

The total weight of the PV panels in this case is 574,9 kg for each tracker, that means a total weight of 5'748.5 kg for the 10 trackers. For transportation, the total weight is a bit higher, namely 6'048.5 kg in total including the packaging.

1.3.3 CROPS

This section presents the inventory referred to the four crops analyzed in this study: tomatoes, onions, faba beans and lettuce. The data presented in the following sections, one for each crop type, refer to the resources used to grow each plant in a field of 1 hectare. The crops are thus treated separately in 4 different scenarios, as if each of them was grown independently. The data are provided by experts of the UPC university, and are estimations based on historical data and on their expertise's assumptions. One of the goals of the present project is to assess how the yield of these crops will actually vary from the base case because of the symbiosis with the PV plant; these data will be directly collected on the field, during the following steps of the project, when the testers will be implemented. In this initial phase of the project, since no information is available on the yield variation, the analysis is performed on the base case, namely on the estimation of the yield without the PV plant (as if only the crop field was implemented). Later on, this analysis will be completed and integrated with the experimental data from the crops to evaluate the system with a broader and more complete view.

Hereafter, all the datasets defined commonly to the four scenarios are described.

Table 1.13. List of datasets used in the crops model

Dataset in SimaPro	Material/process in Ecoinvent 3	Amount
Manure	Manure, solid, cattle {GLO}| market for | Cut-off, U	1 kg
Fertilizer 15 15 15	Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U	0.15 kg
	Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U	0.15 kg
	Potassium fertiliser, as K2O {GLO}| market for | Cut-off, U	0.15 kg
Fertilizer 7 12 40	Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U	0.07 kg
	Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U	0.12 kg
	Potassium fertiliser, as K2O {GLO}| market for | Cut-off, U	0.4 kg
	Sulfur trioxide {RER}| market for sulfur trioxide | Cut-off, U	0.16 kg
Fertilizer 13 0 44	Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U	0.13 kg
	Potassium fertiliser, as K2O {GLO}| market for | Cut-off, U	0.44 kg
Ammonium nitrosulfate 26%	Ammonium sulfate, as N {GLO}| market for | Cut-off, U	0.26 kg
Agrochemical generic	Pesticide, unspecified {RER}| production | Cut-off, U	1 kg
Metalaxil 25% + caolin	Dimethylacetamide {GLO}| market for | Cut-off, U	0.25 kg
Neem oil	Palm oil, refined {GLO}| market for | Cut-off, U	1 kg
Plastic film (bio)	Polyester-complexed starch biopolymer {GLO}| market for | Cut-off, U	1 kg
	Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, U	1/0.976 kg
Water	Tap water {Europe without Switzerland}| market for | Cut-off, U	1 kg
Tractor	Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	MJ
Electricity	Electricity, low voltage {ES}| market for | Cut-off, U	1 kWh

The “Agrochemical generic” item includes several substances that could not be modelled with detail since no specific dataset could describe them consistently. It includes the following substances: Spinosad 48%, Deltametrin 2,5% EW, Tebuconazol 25% EW, Fludioxonil 50% WG, Spirotetramat 10% SC, Fenhexamida 50% WG and Eugenol 3,3% + Geraniol 6,6% + Timol 6,6% CS.

The data provided in the following sections refer to the process of planting each crop in 1 hectare for 1 year, considering the seasonality of each crop.

1.3.3.1 *TOMATO*

The modelling of the tomatoes is made as follows. The generic pesticide, in this case, represents Spinosad 48%.

The yield expected in 1 hectare cultivated only with tomatoes is 23’400 kg. During the implementation of the project, more specific data on the yield will be collected.

Table 1.14. Tomtatoes modelling

Dataset in SimaPro	Amount
Fertilazers	
Manure	10’000 kg
Fertilizer 13 0 44	300 kg
Agrochemical	
Neem oil	1.8 kg
Dimethylacetamide {GLO}| market for | Cut-off, U	0.4 kg
Agrochemical generic	0.211
Others	
Plastic film	0.0132 kg
Seeds	
Tomato seedling, for planting {GLO}| market for tomato seedling, for planting | Cut-off, U	19’500 pieces
Water	
Tap water {Europe without Switzerland}| market for | Cut-off, U	3’450’000 kg
Tractors	

Dataset in SimaPro	Amount
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	6’057 MJ
Electricity	
Electricity, low voltage {ES}| market for | Cut-off, U	506 kWh

1.3.3.2 *ONION*

The modelling of the onions is made as follows. The generic pesticide, in this case, represents Deltametrin 2.5% EW and Tebuconazol 25% EW.

The yield expected in 1 hectare cultivated only with onions is 30’600 kg (direct data will be collected throughout the project implementation).

Table 1.15. Onion modelling

Dataset in SimaPro	Amount
Fertilazers	
Manure	8’000 kg
Fertilizer 13 0 44	150 kg
Agrochemical	
Agrochemical generic	0.58 kg
Others	
Plastic film	0.0132 kg
Seeds	
Onion seedling, for planting {GLO}| market for onion seedling, for planting | Cut-off, U	116’675 pieces
Water	
Tap water {Europe without Switzerland}| market for | Cut-off, U	3’000’000 kg
Tractors	
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	5’864 MJ
Electricity	

Dataset in SimaPro	Amount
Electricity, low voltage {ES}| market for | Cut-off, U	506 kWh

1.3.3.3 *FAVA BEANFava bean*

The modelling of the fava beans is made as follows. The generic pesticide, in this case, represents Spirotetramat 10% SC and Eugenol 3,3% + Geraniol 6,6% + Timol 6,6% CS.

The yield expected in 1 hectare cultivated only with fava beans is 14'000 kg (direct data will be collected throughout the project implementation).

Table 1.16. Onion modelling

Dataset in SimaPro	Amount
Fertilazers	
Fertilizer 13 0 44	200 kg
Agrochemical	
Agrochemical generic	0.256 kg
Others	
Plastic film	0.0132 kg
Seeds	
Fava bean seed, for sowing {GLO}| market for | Cut-off, U	20 kg
Water	
Tap water {Europe without Switzerland}| market for | Cut-off, U	900'000 kg
Tractors	
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	4'786 MJ
Electricity	
Electricity, low voltage {ES}| market for | Cut-off, U	132 kWh

Lettuce

The modelling of the lettuce is made as follows. The generic pesticide, in this case, represents Fludioxonil 50% WG, Spirotetramat 10% SC and Fenhexamida 50% WG.

The yield expected in 1 hectare cultivated only with lettuce is 26’444 kg (direct data will be collected throughout the project implementation).

Table 1.17. Onion modelling

Dataset in SimaPro	Amount
Fertilazers	
Manure	5’000 kg
Fertilizer 13 0 44	85 kg
Agrochemical	
Agrochemical generic	0.8 kg
Others	
Plastic film	0.0132 kg
Seeds	
Grass seed, organic, for sowing {GLO}| market for | Cut-off, U	0.2333 kg
Water	
Tap water {Europe without Switzerland}| market for | Cut-off, U	700’000 kg
Tractors	
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	6’028 MJ
Electricity	
Electricity, low voltage {ES}| market for | Cut-off, U	103 kWh

1.4 IMPACT ASSESSMENT AND INTERPRETATION

In this section, the methods selected for the evaluation and the obtained results are presented.

1.4.1 METHODS

The software used for modelling is SimaPro, PhD version, release 9.1.0.8. The selected datasets are type “Cut off, System”.

The Method used for the LCA assessment is the EF 3.0 Method, developed at the European level within the Environmental Footprint initiative. The 16 environmental indicators encompassed are the following:

- Climate change (kg CO2eq)
- Ozone depletion (kg CFC11 eq)
- Ionising radiation (kBq U-235 eq)
- Photochemical ozone formation (kg NMVOC eq)
- Particulate matter (disease inc.)
- Human toxicity, non-cancer (CTUh)
- Human toxicity, cancer (CTUh)
- Acidification (mol H+ eq)
- Eutrophication freshwater (kg P eq)
- Eutrophication, marine (kg N eq)
- Eutrophication, terrestrial (mol N eq)
- Ecotoxicity, freshwater (CTU eq)
- Land use (Pt)
- Water use (m^3 depriv)
- Resource use, fossils (MJ)
- Resource use, minerals and metals (kg Sb eq)

1.4.2 RESULTS OF SYSTEM ELEMENTS

Hereafter, the results obtained from the modelling are presented for each of the elements analyzed.

1.4.2.1 *STRUCTURE*

This section reports the results obtained for the scenarios previously described. The values obtained for each indicator are reported in Table 19 per functional unit (FU1), namely 1 tracker.

Table 1.18. Results obtained in the scenarios.

Impact category	Unit (per FU)	Steel	Steel 60y	Wood	Wood 15y	Wood coat
Climate change	kg CO2 eq	1’189.3	763.1	893.6	1150.1	972.0
Ozone depletion	kg CFC11 eq	1.28E-04	9.32E-05	1.09E-04	1.46E-04	1.15E-04
Ionising radiation	kBq U-235 eq	159.39	96.81	132.26	177.41	137.68
Photochemical ozone formation	kg NMVOC eq	5.52	3.53	4.72	6.44	4.98
Particulate matter	disease inc.	1.00E-04	6.13E-05	1.29E-04	2.09E-04	1.33E-04
Human toxicity, non-cancer	CTUh	2.34E-04	1.19E-04	1.14E-04	1.26E-04	1.16E-04
Human toxicity, cancer	CTUh	1.03E-05	5.28E-06	5.18E-06	5.88E-06	5.32E-06
Acidification	mol H+ eq	6.84	4.19	6.04	8.31	6.91
Eutrophication, freshwater	kg P eq	0.74	0.40	0.52	0.66	0.54
Eutrophication, marine	kg N eq	1.56	1.00	1.44	2.01	1.56
Eutrophication, terrestrial	mol N eq	16.65	10.56	15.74	22.20	16.42
Ecotoxicity, freshwater	CTUe	60’708	32’975	49’164	63’260	50’959
Land use	Pt	7’088	4’762	140’460	277’051	142’058
Water use	m3 depriv.	402.62	224.96	368.23	509.30	420.52
Resource use, fossils	MJ	16’213.0	10’556.8	12’867.3	16’890.6	13’677.2

Impact category	Unit (per FU)	Steel	Steel 60y	Wood	Wood 15y	Wood coat
Resource use, minerals and metals	kg Sb eq	3.15	1.58	2.23	2.24	2.23

In order to compare these scenarios in a visual way, the steel scenario has been taken as the base scenario, namely the reference one. Consequently, for each indicator, all the values were evaluated as percentage values of the base scenario.

The spider diagram in Figure 1.7 and Figure 1.8 show the results obtained for 15 of the 16 indicators encompassed in the study (excluded the Land Use indicator). It appears that the steel scenario presents higher impacts than the wood scenario in almost all the impact categories considered, with the exception of the particulate matter. The impacts are significantly lower, around half of the ones in the steel scenario, in the case of human toxicity (both the cancer and non-cancer one). The other indicators present around 70-90% of the impacts than in the base case, while in a few cases the impacts are not significantly reduced: the impacts on terrestrial eutrophication are only 95% of the ones in the steel scenario, while 92% in the cases of marine eutrophication and water use. Finally, an increase of particulate matter release can be observed, up to 129%. This is due to the use of the wood; in fact, the glued laminated timber dataset includes wood processing with significant impacts on this indicator.

On the other hand, if the wood parts need to be replaced after 15 years the results significantly change: in 10 of the 15 indicators the impacts are higher than in the steel scenario. The most noticeable indicator is the particulate matter one, where the impacts more than double, while for eutrophication (terrestrial and marine) the increase is around 30%. A decrease in the impacts can still be observed for the human toxicity indicators (54-57% of the initial impacts) and for climate change (slightly, around 97%), eutrophication – freshwater (89%), and resource use, minerals and metals, where the impacts drop to 71% of the steel scenario ones. In the other scenario analysed for wood, namely the case where wood components are re-painted with a protective coating every 7-8 years and thus are not replaced, the impacts are only slightly higher than in the base case analysed for wood. The impacts in this case are similar to the ones obtained for the steel scenario for the water use, eutrophication (terrestrial and marine) and acidification scenarios.

To conclude, it is interesting to assess can be observed that the impacts of the steel scenario are significantly lower if we consider that the steel components are re used for further applications after the end of the system lifecycle, without re-processing, and so if we allocate their impacts to both systems, namely the steel scenario with 60-years components. In this case, the impacts are reduced in all the impact categories analysed, with reductions to 51-73% if compared to the steel scenario.

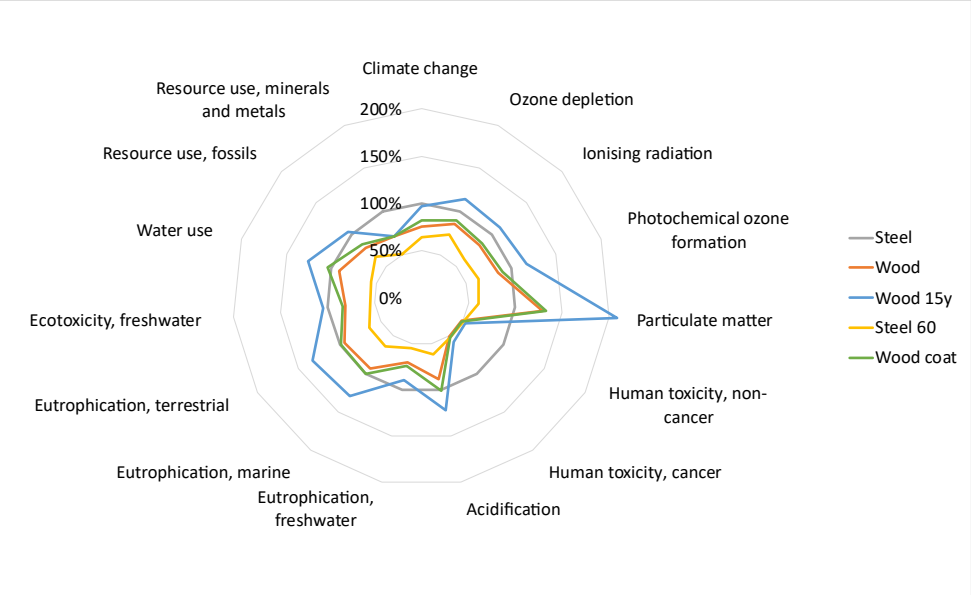
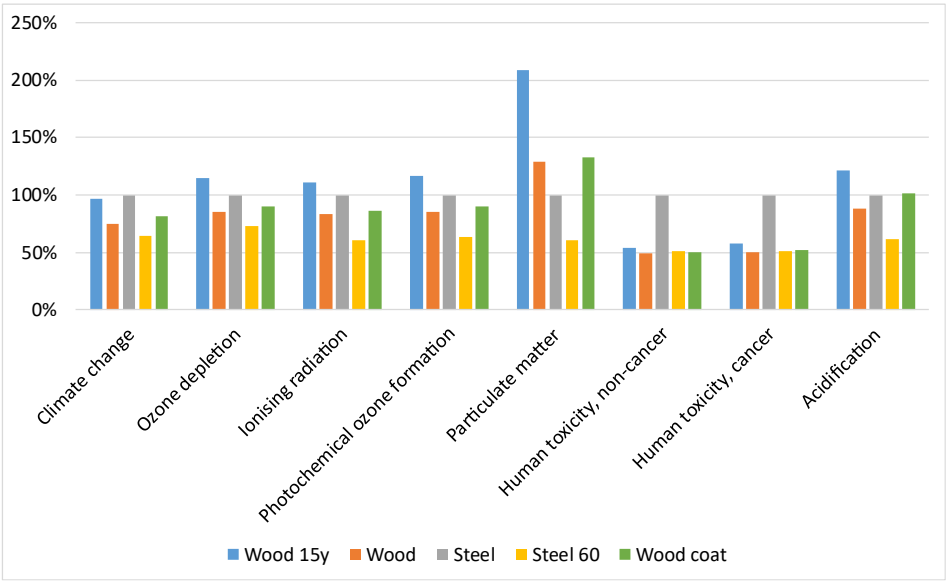


Figure 1.6. Relative results of the 5 scenarios, compared to the steel scenario, radar chart



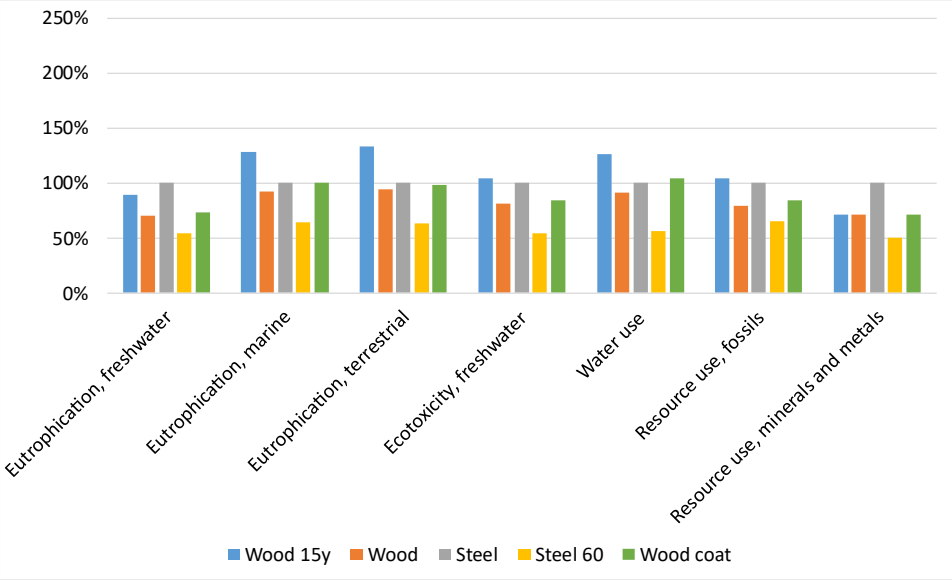


Figure 1.7. Relative results of the 5 scenarios, compared to the steel scenario, bar chart

On the other hand, the land Use indicator behaves differently. This indicator evaluates the quality of soil, and its variation due to the processes needed to realize the product/process under assessment. The methodology for the calculation of this change has been developed by the Joint Research Center, starting from LANCA® v 2.5 as baseline model.

The impact of using wood instead of steel in this case is higher, and even more if the wood poles are expected to be replaced during the system lifetime. The values related to this indicator are depicted in Figure 1.7.
Another consideration to be made is related to the wood availability. In fact, the request of wood for this type of application can be significant considering that many sub-components are expected to be replaced (the foundations and the beams that hold the PV panels). Therefore, the application of this solution on a large scale would require an important amount of wood.

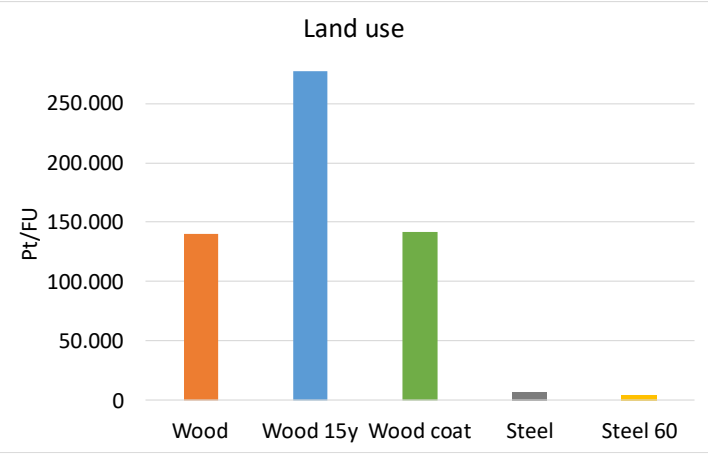


Figure 1.8. Land use indicator results

In the next sections, the details of each scenario's results are reported.

Steel scenario

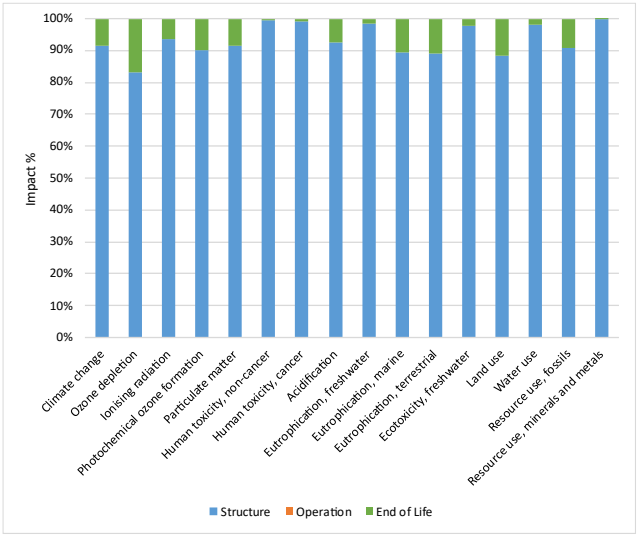


Figure 1.9. % weight of each stage on the total impacts, steel scenario

Figure 1.9 reports the relative weight of each stage of the lifetime on the total impact on each impact category. It can be observed that, for all categories, the structure is responsible of the majority of impacts (from around 83% in case of ozone depletion to 99.9%, in case of resource use, mineral and metals). This lifecycle stage includes the operations from the collection and transportation of all the materials to the assembly and transportation of the components to the site. A smaller responsibility on the total impacts is due to the end of life stage, namely the dismantling, transportation of the materials to the treatment plants and the treatment of the waste itself. No impacts are associated to the operational stage, since no operations or replacements are encompassed in this case.

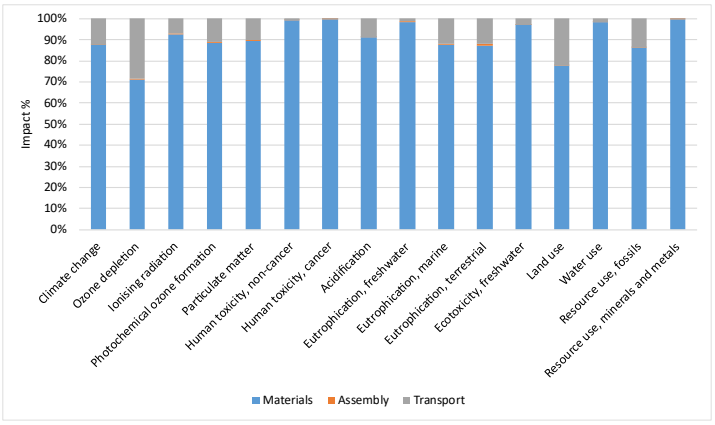


Figure 1.10. % weight of each sub-stage on the structure, steel scenario

Deepening this aspect, with a focus on the "structure" stage, it can be noticed that it is made by three main components: the actual production of the structure materials for the tracker, the assembly phase and the transport of the structure to the site.
The phase in charge of almost all the impacts is the one represented by the materials. This includes the materials extraction, the transportation to the manufacturer's sites, and the processing of these materials.

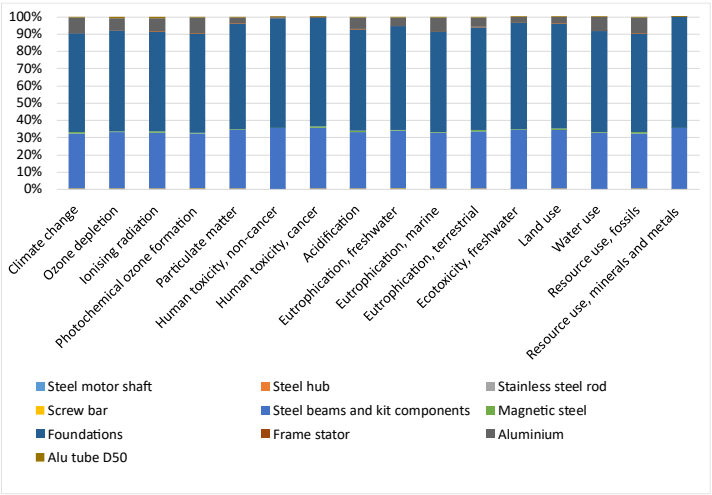


Figure 1.11. % wight of each sub-element on the tracker, steel scenario

Zooming on the materials, that showed to be the responsible of most impacts, it can be noticed that between 60% and 70% of the impact is represented by the foundations, and 30% by the steel beams and kit components. These are the elements for which the potential replacement with wood components is assessed. This is an important aspect to be taken into account when comparing the scenarios.

Steel scenario, 60 years

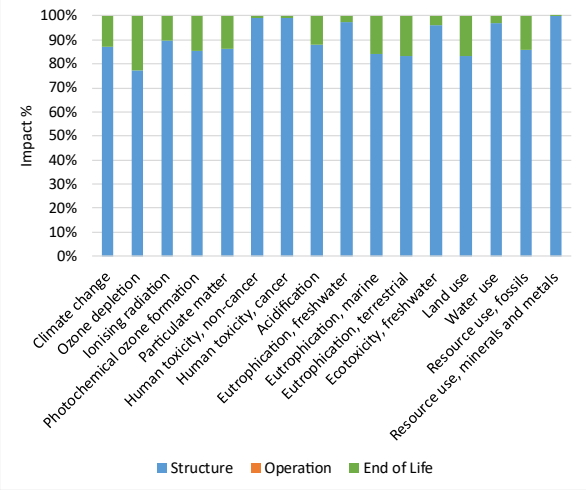


Figure 1.12. % weigh of each stage on the total impacts, steel 60 years scenario

This scenario is a variation of the previous one. The difference is noticeable in terms of absolute values, as seen in the previous tables and diagrams, but not in the relative ones, as can be seen in Figure 1.12.

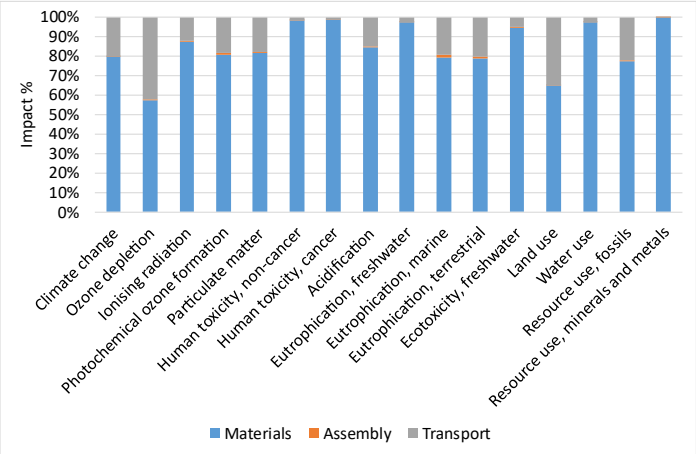


Figure 1.13. % weight of each sub-stage on the structure, steel 60 years scenario

It should be considered that the impacts of the materials used (steel structural components) is reduced by 50%, since the components are used for further applications and their impacts are allocated to the different systems; therefore, the impacts of the materials used have a lower weight than the one observed in the steel scenario on the total, while the relative impact of transport on the total is higher, since the total weight of the structure is the same. In any case, for all the indicators analysed the materials are responsible of the majority of the impacts.

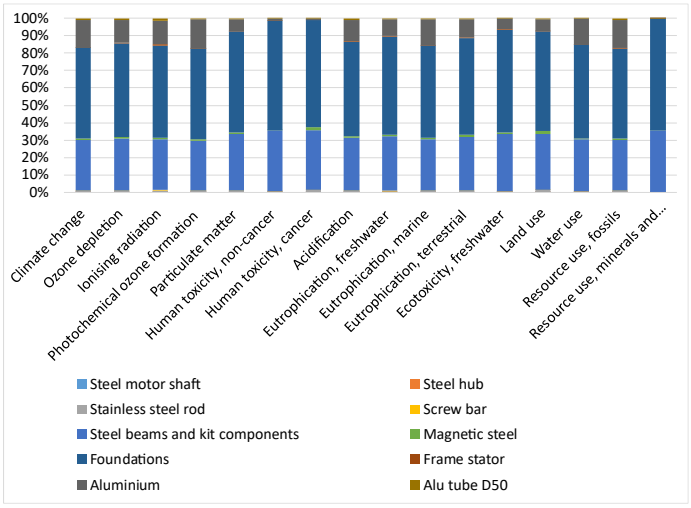


Figure 1.14. % weight of each sub-element on the tracker, steel scenario

The details of the sub-components of the structure are not significantly different than the ones observed for the steel scenario. Also in this case, between 80% and 100% of the total impacts is related to the materials that compose the steel beams and kit components, and the foundations (only this component is responsible of between 50% and 64% of the total impacts, in all the indicators assessed.

Wood scenario

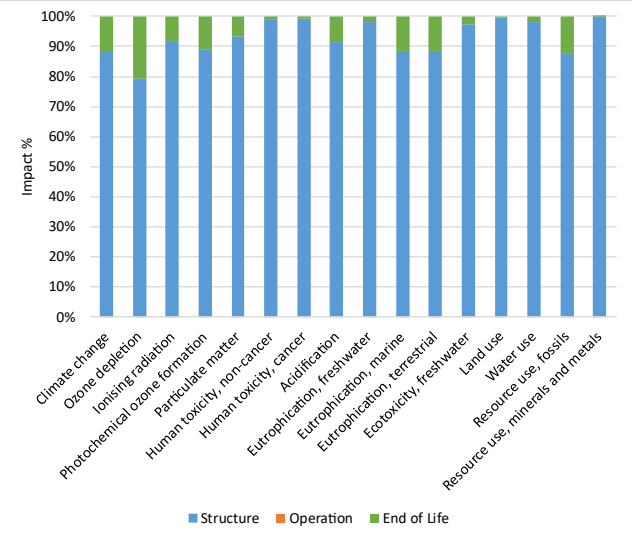


Figure 1.15. % weight of each stage on the total impacts, wood scenario

In Figure 1.15 the relative weight of each stage of the lifetime for each impact category are presented.
Also in this case, as seen for the steel scenario, the operation stage is not responsible of any impact, considering that no activities nor substitutions have to be carried out in this scenario.
The majority of impacts are associated to the structure itself, while only a small amount (maximum 20% of the total) to the end of life of the components.

Compared to the steel scenario, the weight of the structure on the total impacts in many of the indicators under assessment appears to be slightly lower. This consideration, in any case, should be made keeping in mind that these are relative values, while the absolute values, as seen in the previous diagrams and tables, are usually lower than in the steel scenario.

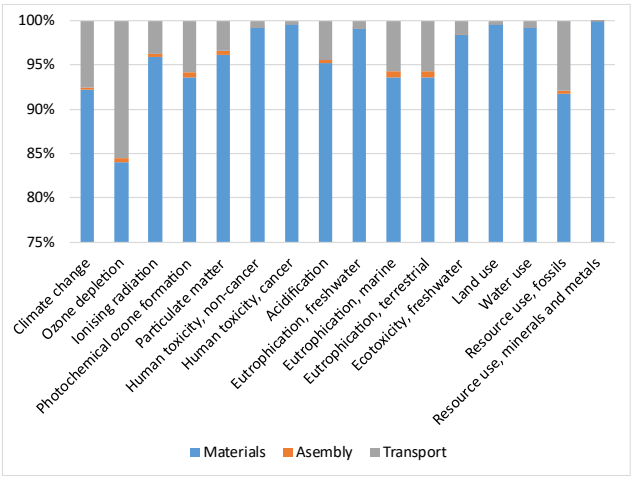


Figure 1.16. % weight of each sub-stage on the structure, wood scenario

As seen in the previous scenario, considering the structure only, three main components can be identified: the actual production of the structure materials for the tracker, the assembly phase and the transport of the structure to the site.
While the transport only counts for a very small percentage of the impact of the structure, the main contribution is given by the materials used (68% for ozone depletion, and above 95% in several other cases).

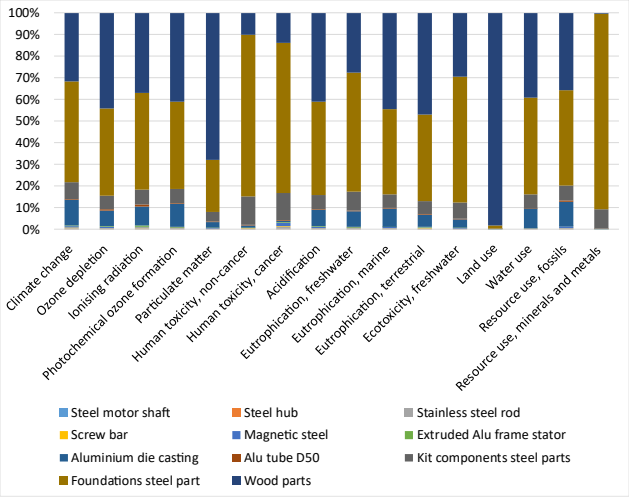


Figure 1.17. % weight of each sub-element on the tracker, wood scenario

For what concerns materials, it can be observed that the wood elements are the ones responsible of an important percentage of the impacts. They represent almost all the impacts related to land use (98.2%), while 68% of the ones of the particulate matter indicator. For the other impact categories, the wood part count for 30%-45% of the total. The indicators for which these elements play a minor role are the human toxicity ones (10% for the non-cancer indicator, and 13.7% for the cancer one). Finally, the resource use, minerals and metals indicator does not see a crucial role of the wood elements, that only count for 0.4% of the total impacts (differently from what observed in the case of steel components).

Wood scenario, 15 years replacement

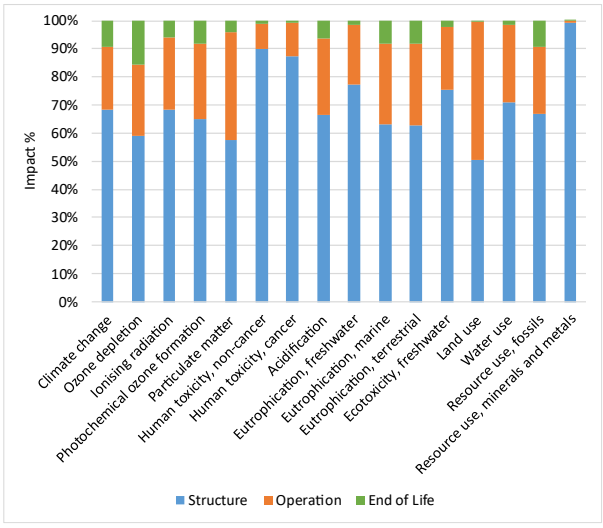


Figure 1.18. % weight of each stage on the total impacts, wood replacement scenario

This scenario, differently from the previous ones, includes the operation stage. In fact, the wood elements are supposed to be replaced after 15 years of operation, because of the strength requirements of the structure. Therefore, in the operation stage the new wood elements production, the assembly and their disposal are considered. This stage counts for around 9-38% of the total impacts, depending on the indicator analysed, with the extreme peaks of 0.4% on case of the resource use minerals and metals, and 49.3% of the land use ones. This aspect is in line with the considerations made in the initial comparison of the impacts; in fact, the land use is higher in case of elements made from wood than ones made from metals.

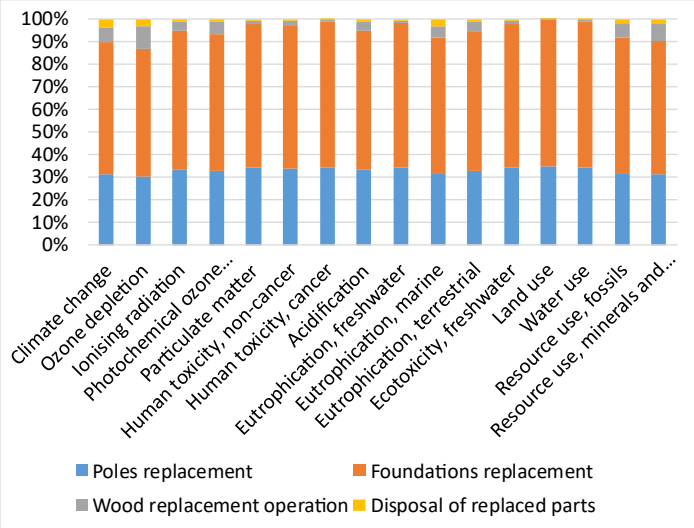


Figure 1.19. % weight of the operation stage, wood replacement scenario

The operation stage consists in the production of the wood elements needed to replace the original ones after 15 years, the dismantling of the structure to replace the specific parts, and the installation of the new components. In addition, the end of life treatment of the original wood components is considered.

In this case, it can be observed that, from the selected environmental categories perspective, most of the impact is due to the production of the new wood components (beams and foundations), up to between 87% and 99.9% of the total. A lower percentage is due to the operation processes, namely the mounting and dismounting of the structure to install the new wood elements, in form of electricity consumptions and use of machinery fuelled by diesel. These percentages are up to 9.6% of the total impacts (in the case of ozone depletion indicator), while are lower in the other ones.

Finally, a small portion of the impacts is due to the disposal of the original wood parts, with a peak of 3.8% for climate change indicator, 3.4% and 3.3% for marine eutrophication and ozone depletion, and lower values for all the other ones.

Wood scenario, with protective coating

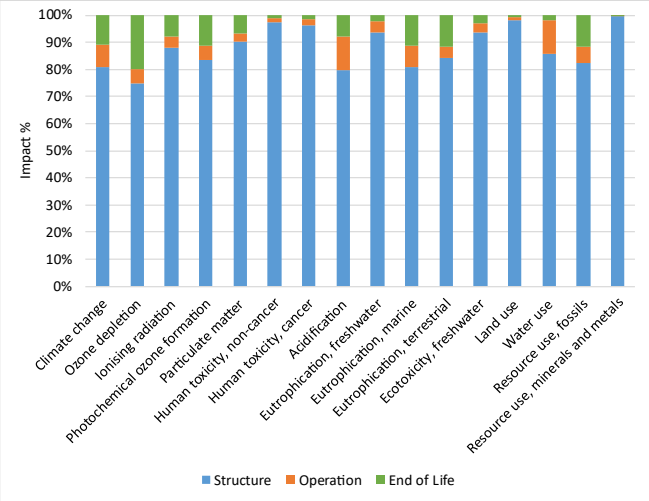


Figure 1.20. % weight of each stage on the total impacts, wood coating scenario

Also this scenario includes the operation stage. In fact, the wood elements are expected to be painted with a protective coating every 7-8 years, as suggested by the experts, and thus 4 times along the total system lifetime, modelled with an alkyd paint.

This stage represents around 8-12% of the impacts for some of the indicators analysed, such as acidification, water use, climate change and eutrophication, marine. In the case of other indicators, the weight of this stage on the total impacts is more limited.

In general, it can be said that the difference with the basic wood scenario is quite limited, with a few percentage point increase. In the case of some indicators, namely the ones mentioned beforehand (water use, climate change and eutrophication, marine), the difference is noticeable, with around 8%-14% increase in the total impacts, due to the use of the painting.

1.4.2.2 *PV PANELS*

The results obtained for the PV panels analysis are reported in the Table 1.19. The results are reported first of all as a whole, namely for the whole PV system analyzed. In addition, they are reported per functional unit, as described in section 1.2.2.2.

These considerations were made building on the fact that each of the 10 trackers holds panels for a total nominal power of 6 kW, and that the plant is expected to be installed in Baix Llobregat, close to Barcelona. Therefore, the estimation of the total annual electricity generation has been done through the PVGIS online tool, developed by the JRC. The simulation foresees a generation of 9.396 MWh/year per tracker, for a total of 2'818.8 MWh along the 30 years of operation for the whole plant (10 trackers). The total results obtained have thus been divided per the whole electricity generation, in order to obtain the impacts per kWh (UF2).

Standard PV scenario

Table 1.19. Standard PV panels, total results

Impact category	**Unit**	**Total impacts for the whole plant**	**Impact per declared unit**
Climate change	kg CO2 eq	80'346	0.029
Ozone depletion	kg CFC11 eq	7.65E-03	2.72E-09
Ionising radiation	kBq U-235 eq	5'873	2.08E-03
Photochemical ozone formation	kg NMVOC eq	314.4	1.12E-04
Particulate matter	disease inc.	6.49E-03	2.30E-09

Impact category	Unit	Total impacts for the whole plant	Impact per declared unit
Human toxicity, non-cancer	CTUh	3.42E-03	1.21E-09
Human toxicity, cancer	CTUh	1.01E-04	3.57E-11
Acidification	mol H+ eq	505.0	1.79E-04
Eutrophication, freshwater	kg P eq	41.3	1.47E-05
Eutrophication, marine	kg N eq	91.9	3.26E-05
Eutrophication, terrestrial	mol N eq	909.4	3.23E-04
Ecotoxicity, freshwater	CTUe	3’317’588	1.177
Land use	Pt	297’044	0.105
Water use	m3 depriv.	76’175	0.027
Resource use, fossils	MJ	944’729	0.335
Resource use, minerals and metals	kg Sb eq	9.6	3.40E-06

Figure 1.21 reports the percental part of each stage of the lifetime on each indicator considered. It can be observed that the materials used to build the panels are responsible for most of the impacts, between 56% and 95%, depending on the indicator.

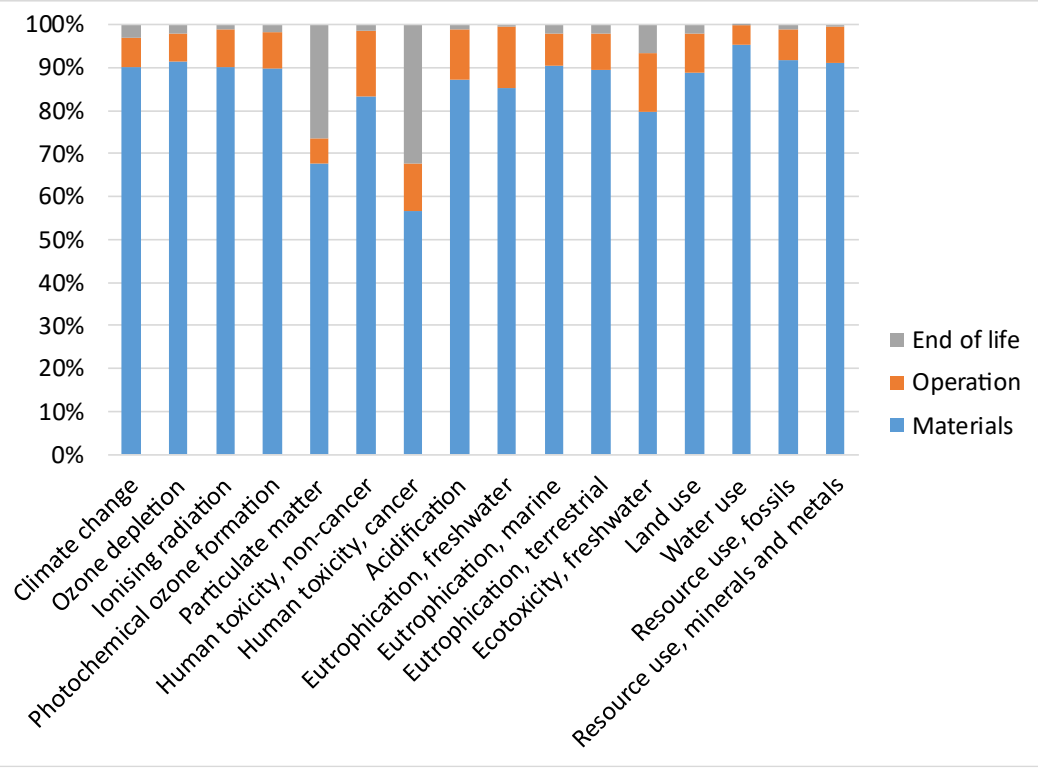


Figure 1.21. % weight of each stage on the total impacts, standard PV panels

Only focusing on the materials stage, it could be observed that, out of its impacts, the majority (between 84% and 99%) is related to the production of the PV panels (Figure 1.22). These are mainly due to the cell production, as can be seen in Figure 1.23.

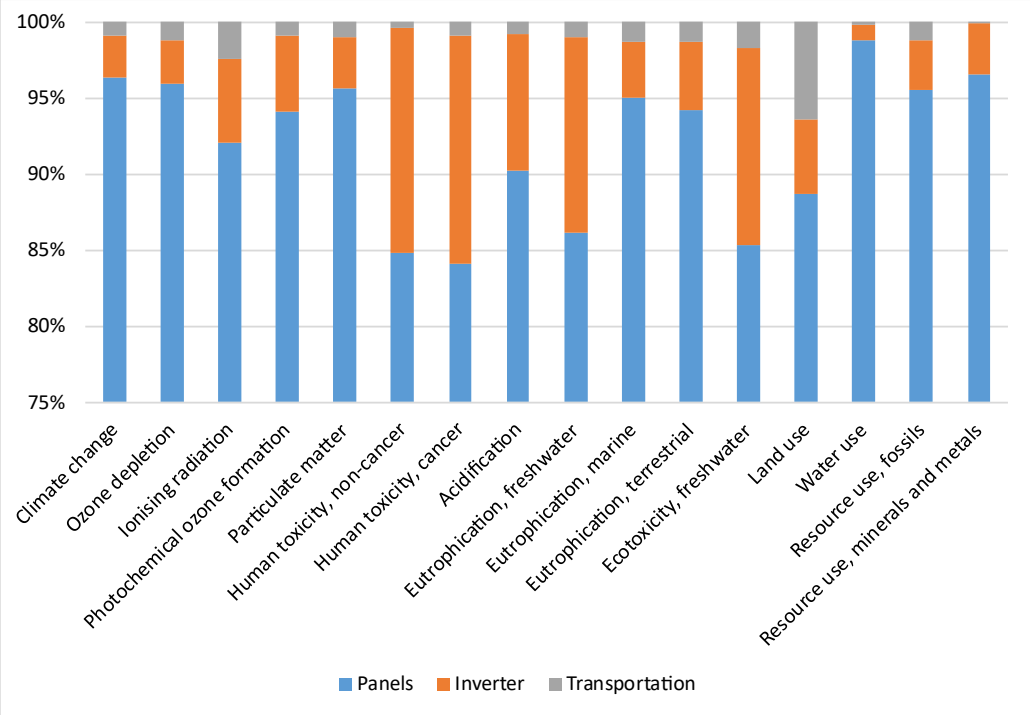


Figure 1.22. % weight of the standard PV panels materials

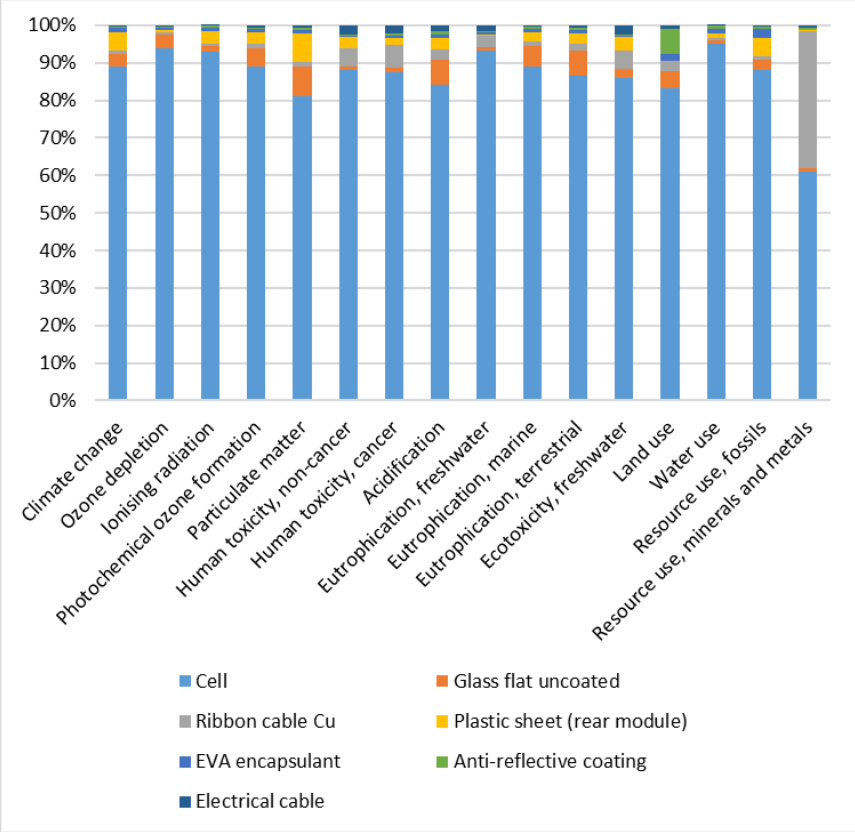


Figure 1.23. % weight of impacts for 1 standard PV module

Semi-trans PV scenario

The second case described in section 1.3.2.2, namely the scenario in which the PV modules are made with less PV cells, is reported hereafter.

Table 1.20. Semi-trans PV panels, total results

Impact category	Unit	Total impacts for the whole plant	Impact per declared unit
Climate change	kg CO2 eq	61’066	0.022
Ozone depletion	kg CFC11 eq	5.35E-03	1.90E-09
Ionising radiation	kBq U-235 eq	4’184	1.48E-03
Photochemical ozone formation	kg NMVOC eq	239.0	8.48E-05
Particulate matter	disease inc.	5.51E-03	1.96E-09
Human toxicity, non-cancer	CTUh	2.73E-03	9.69E-10
Human toxicity, cancer	CTUh	8.91E-05	3.16E-11
Acidification	mol H+ eq	410.1	1.45E-04
Eutrophication, freshwater	kg P eq	32.2	1.14E-05
Eutrophication, marine	kg N eq	70.1	2.49E-05
Eutrophication, terrestrial	mol N eq	708.6	2.51E-04
Ecotoxicity, freshwater	CTUe	2’741’551	0.973
Land use	Pt	233’583	0.083
Water use	m3 depriv.	50’373	0.018
Resource use, fossils	MJ	710’798	0.252
Resource use, minerals and metals	kg Sb eq	7.7	2.74E-06

The following diagrams report the specific results obtained for the semi-trans PV panels, as done for the standard case. The difference that can be noted with the other PV scenario is that, since the panels used are less than in the other case, the weight of materials is lower on the total. Similarly, when assessing the materials it can be observed that the total weight of the panels is reduced, while the inverter and transport have a more important role due to the lower presence of panels cells. The same logic applies to the modules, where the responsibility of cells on the total impacts is lower since, as said, less cells are used in each module.

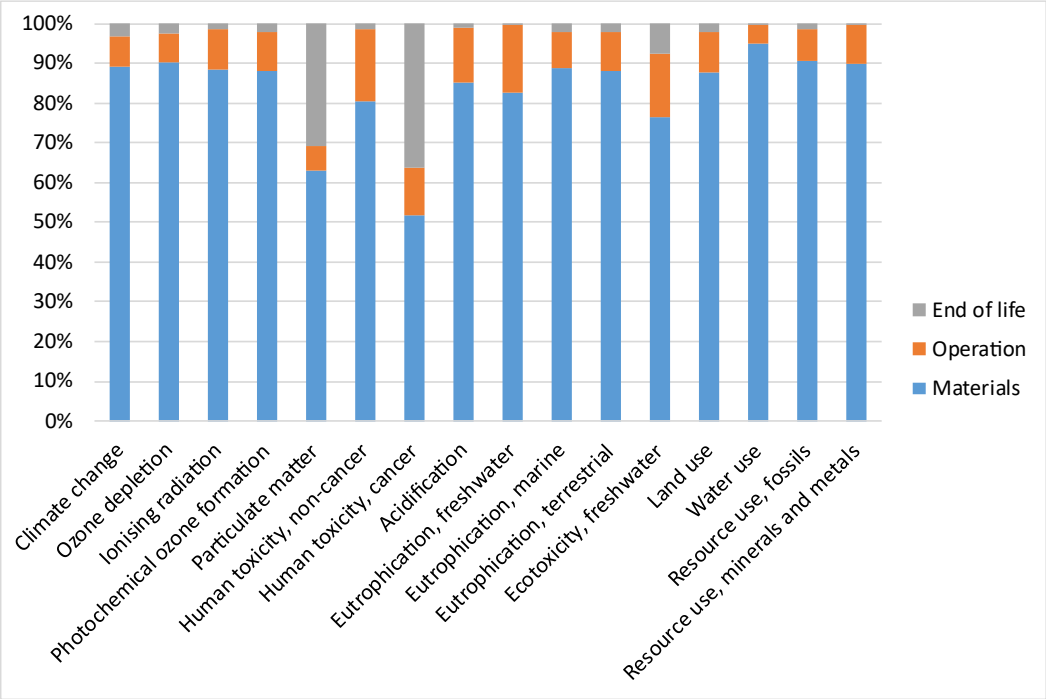


Figure 1.24. % weight of each stage on the total impacts, semi-trans PV panels

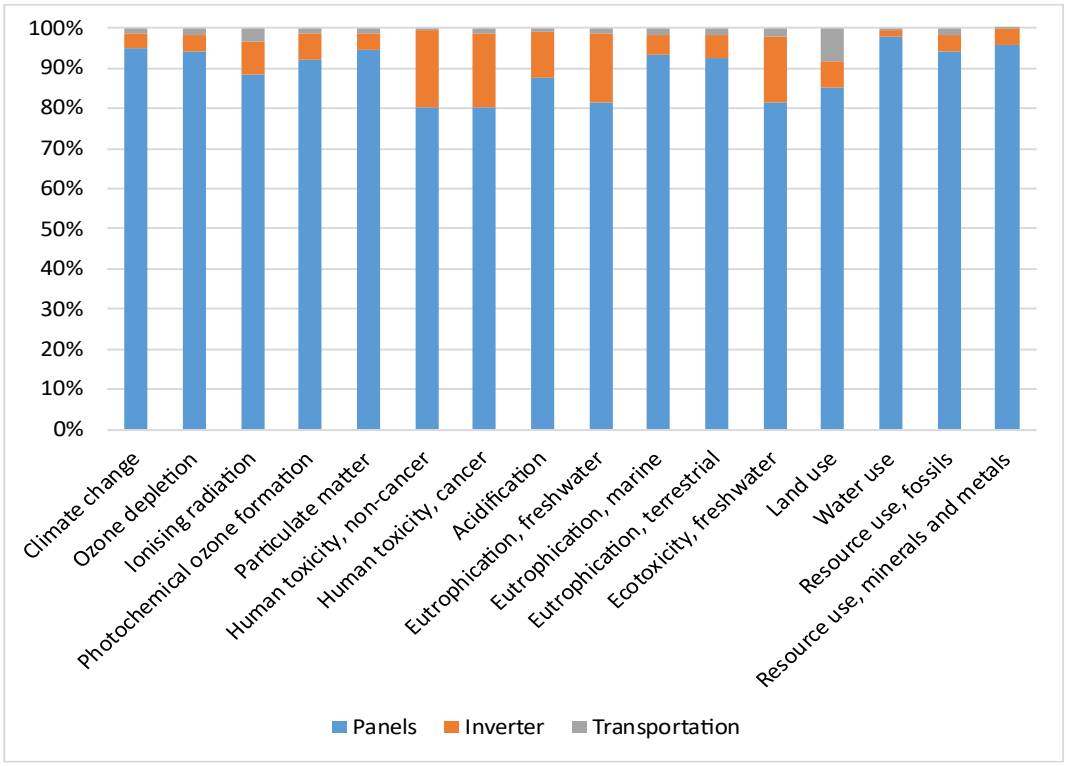


Figure 1.25. % weight of impacts for the semi-trans PV panels materials

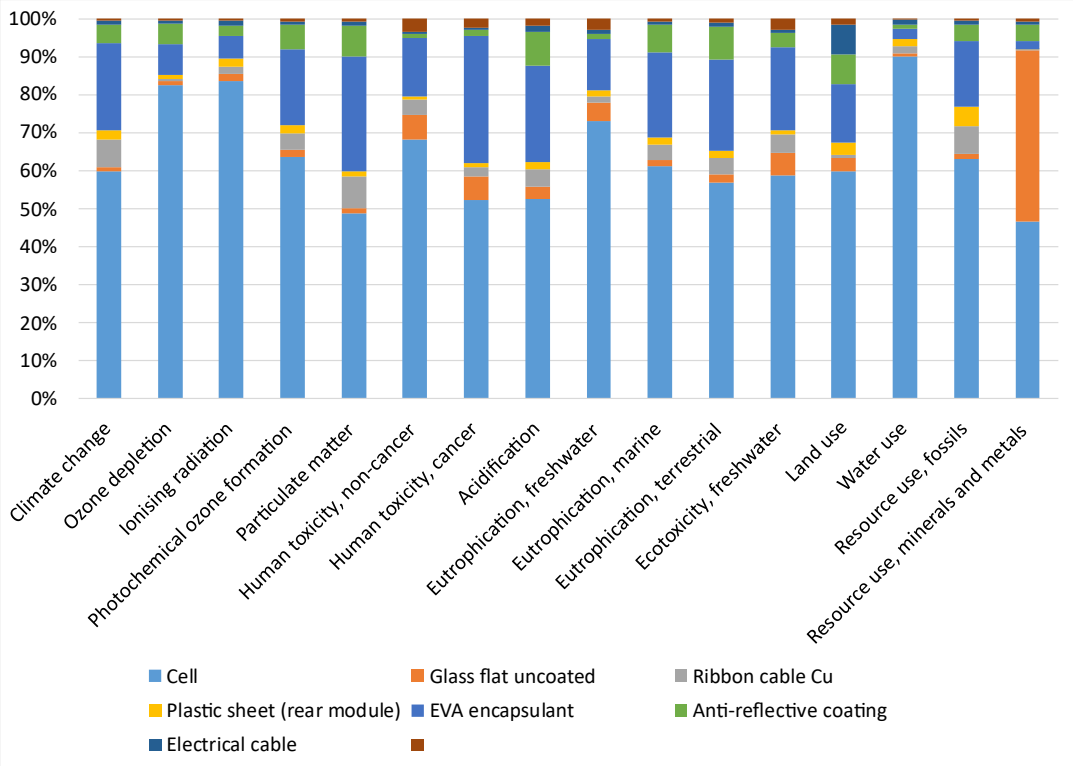


Figure 1.26. % weight of impacts for 1 semi-trans PV module

1.4.2.3 *Crops*

This section reports the results obtained for the scenarios previously described. The values obtained for each indicator are reported in Table 1.21 per functional unit (FU3), namely 1 kg of crops (estimated).

Table 1.21. Results obtained in the 4 scenarios, per-kg of crops

Impact category	Unit (per FU)	Tomato	Onion	Fava bean	Lettuce
Climate change	kg CO2 eq	0.145	0.082	0.086	0.046
Ozone depletion	kg CFC11 eq	1.26E-08	1.04E-08	1.10E-08	6.75E-09
Ionising radiation	kBq U-235 eq	0.026	0.018	0.014	0.006
Photochemical ozone formation	kg NMVOC eq	5.88E-04	4.62E-04	5.63E-04	3.35E-04
Particulate matter	disease inc.	5.07E-09	5.47E-09	4.13E-09	2.00E-09
Human toxicity, non-cancer	CTUh	4.61E-09	3.34E-09	3.25E-09	1.70E-09
Human toxicity, cancer	CTUh	1.77E-10	1.26E-10	1.10E-10	5.24E-11
Acidification	mol H+ eq	7.85E-04	7.85E-04	6.98E-04	3.62E-04
Eutrophication, freshwater	kg P eq	5.13E-05	3.42E-05	3.13E-05	1.41E-05
Eutrophication, marine	kg N eq	1.97E-04	1.92E-04	1.98E-04	1.11E-04
Eutrophication, terrestrial	mol N eq	2.22E-03	2.66E-03	2.09E-03	1.24E-03
Ecotoxicity, freshwater	CTUe	2.55	1.73	2.05	0.91
Land use	Pt	2.19	0.88	1.11	0.55
Water use	m3 depriv.	6.39	4.24	2.79	1.15

Impact category	Unit (per FU)	Tomato	Onion	Fava bean	Lettuce
Resource use, fossils	MJ	2.00	1.20	1.16	0.61
Resource use, minerals and metals	kg Sb eq	3.61E-06	2.68E-06	4.11E-06	2.08E-06

In this case, the scenarios are not expected to be compared in terms of impacts, since the crops are not alternatives to be selected but rather different available options. In general, it can be observed that tomatoes are characterized by a higher impact than the others, while lettuce is the one with the lowest impacts.

In order to understand the causes of the impacts in each case, the detailed results are reported hereafter.

Tomato

In the case of tomatoes, in most of the indicators the majority of the impacts are due to the irrigation and to the burning of fuels to operate the tractors. It should be noted that the water consumption considered is an estimation that builds on average values; in case of rainy years, the water amount needed can be significantly lower. In any case, considering the trend of drought seasons that have been characterizing the late years, the water for irrigation is expected to be needed.

As expected, different indicators present different weights of impact. For example, the water use indicator is almost only related to the irrigation activity, while the land use indicator is characterized by the impact of the seeds production. This observation is valid for all the scenarios presented.

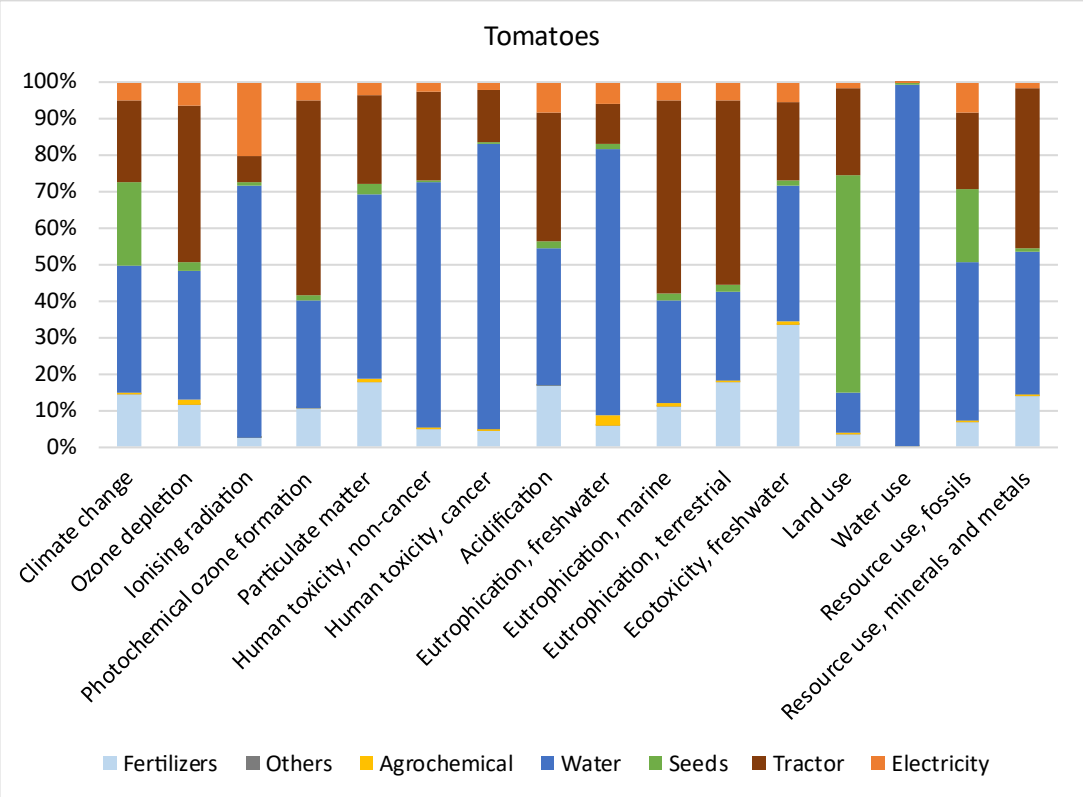


Figure 1.27. Results, tomatoes

Onions

Regarding onions, as seen for the tomatoes, the impacts are mainly related to the water consumption for irrigation and to the use of trucks. In addition, an important portion of the impacts is in this case is due to the production of the seeds.

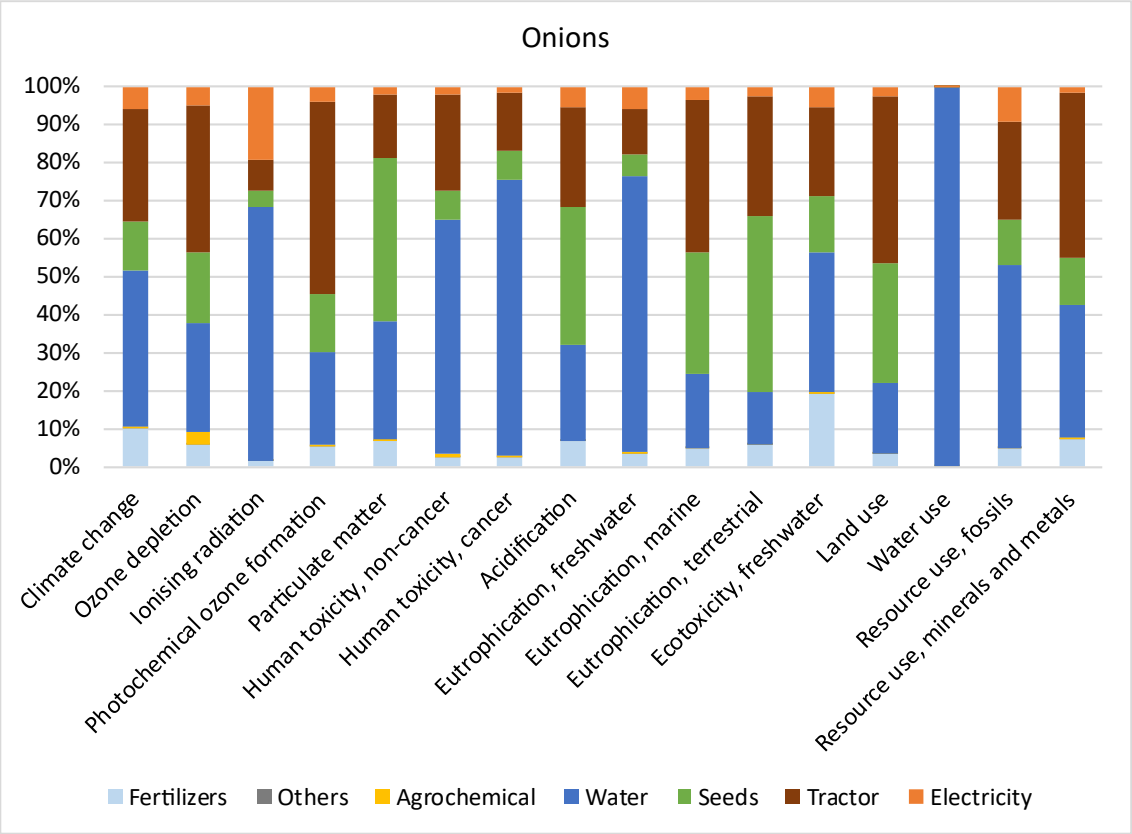


Figure 1.28. Results, onions

Fava bean

This scenario is characterized by important impacts in terms of agricultural machinery and, following, water consumption. It can be observed that in this case the impact of fertilizers is noticeable, especially for what concerns the category of ecotoxicity, freshwater, where it represents almost 40% of the total impacts.

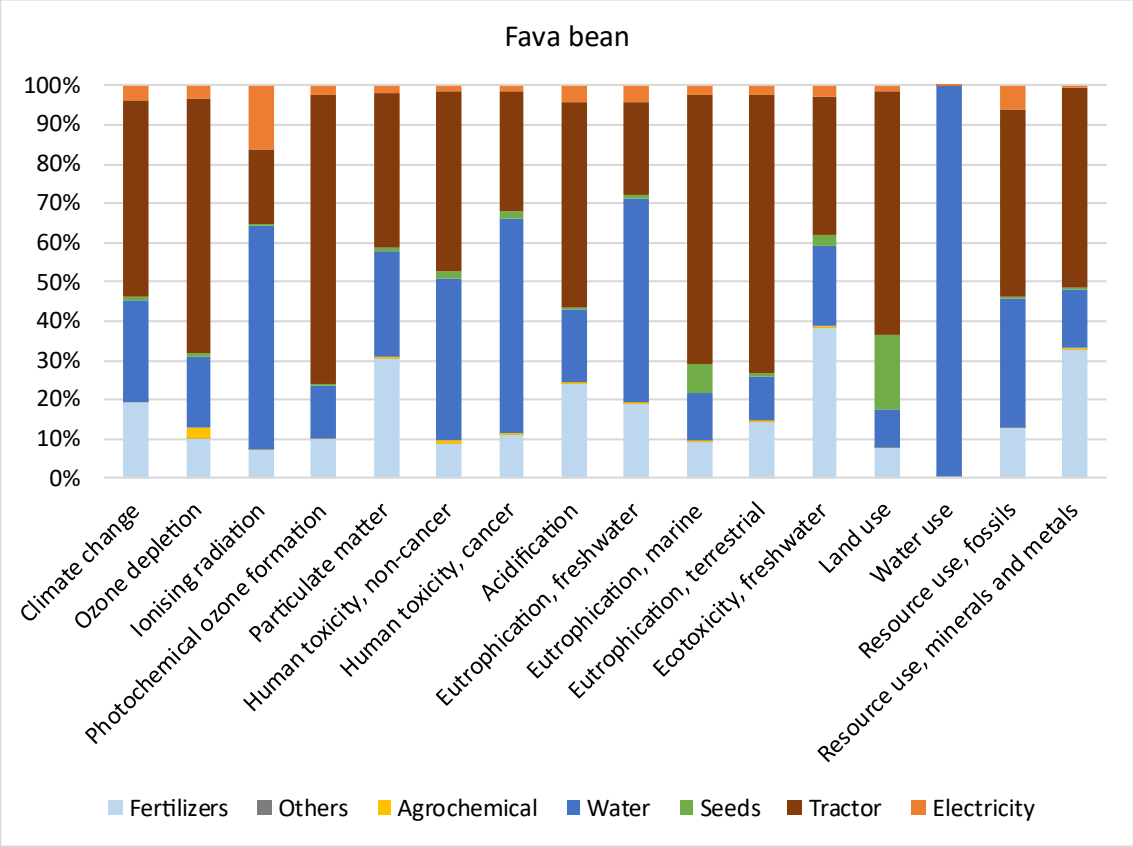


Figure 1.29. Results, fava bean

Lettuce

Most of the impacts are due, in the case of lettuce, to the use of trucks and agricultural machinery. It should be noted that in absolute terms the impacts of this activity are similar for all the crop types. In this case, since the total impacts are lower than in the others, the relative impact of trucks is higher. Following, it can be noticed that, as in the other scenarios, the water consumption plays an important role in the total impact generation.

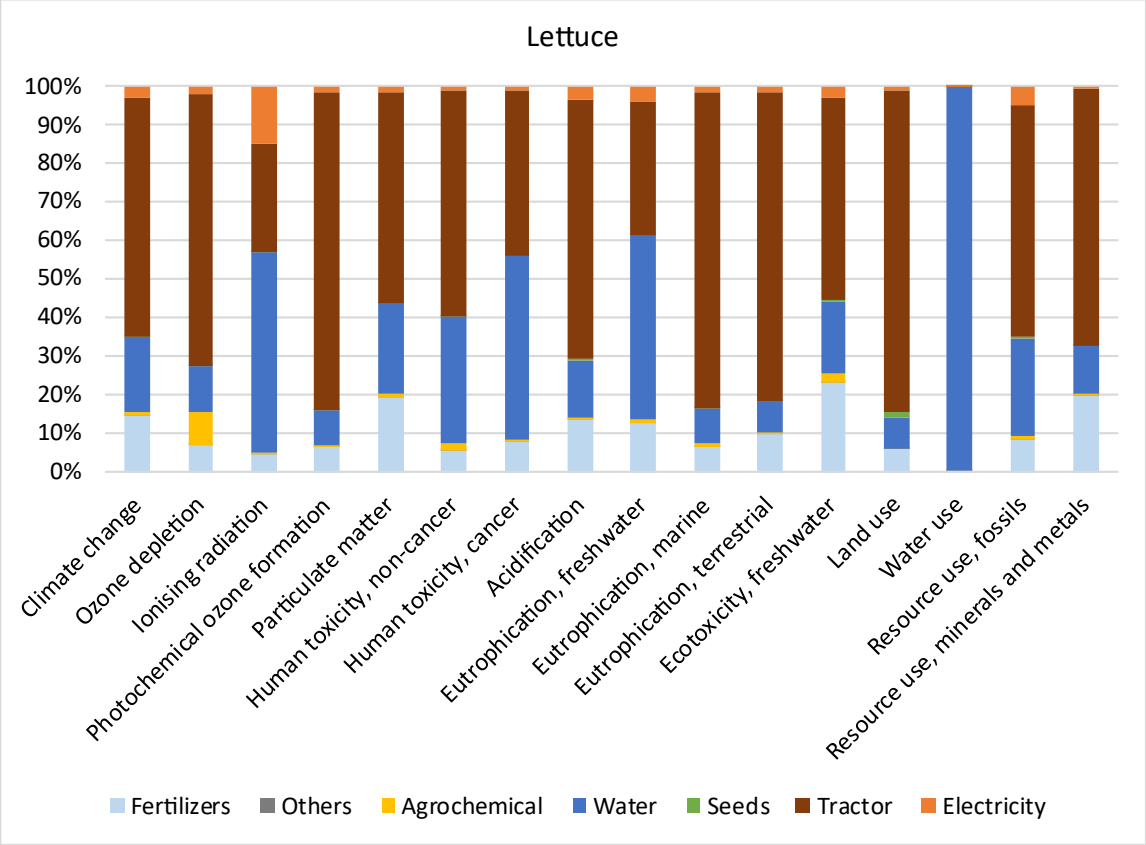


Figure 1.30. Results, lettuce

1.4.3 RESULTS OF SYSTEM CONFIGURATIONS

This section aims at evaluating the total impact of the agrivoltaics plant, by combining the elements previously analyzed in different scenarios. More specifically, the combination of PV structure and panels will be evaluated. As previously mentioned, direct data on the materials needed to grow the crops and the final yield will be collected during the implementation of the project; therefore, this element will be added to the combination of the scenarios once the data will be available (especially important are data on the yield).

The combination is evaluated both for the specific configuration analyzed in the SYMBIOSYST project and for the potential application of such configuration to a 1-hectare field.

1.4.3.1 *SYMBIOSYST CONFIGURATION*

The SYMBIOSYST project encompasses, as described, a use case where 10 trackers are used.
More specifically, two different sub-sections are foreseen, as illustrated in Figure 1.31:

- 5 trackers with opaque modules (standard PV case), with a distance between trackers of 5.9 m;
- 5 trackers with the partially translucent modules (semi-trans PV case), where the distance between the trackers is shorter, namely 4.1 m.

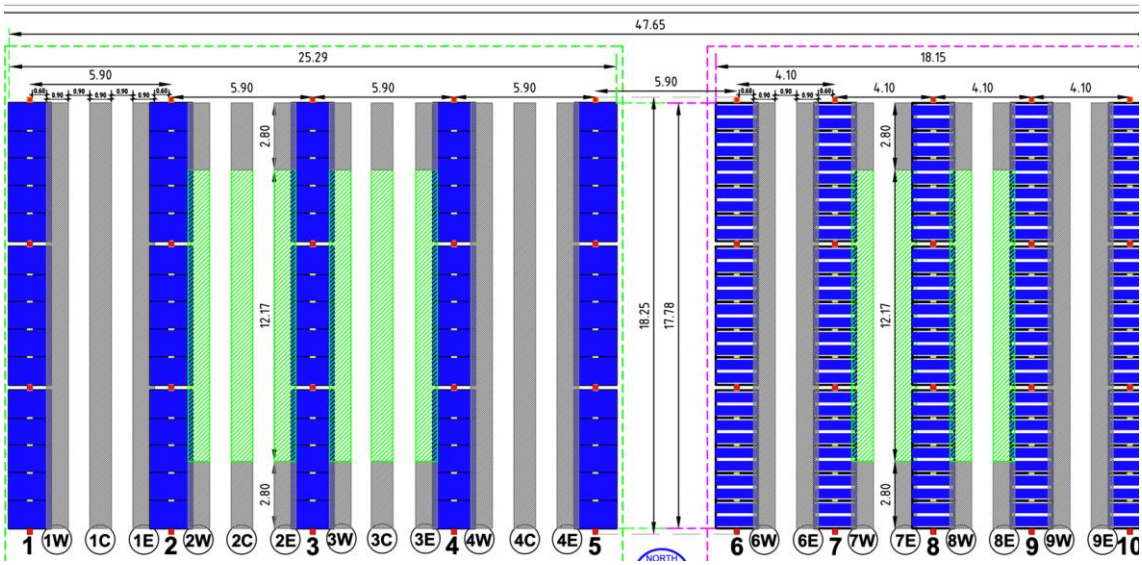


Figure 1.31. SYMBIOSYST configurations

For each of the two configurations the impacts on the selected categories are evaluated. In this case, the functional unit considered has to be common for the two components of the system and is 1 kWh generated by the plant (UF 4). In this case the distance between the trackers does not have an impact on the results, since there is not a space limitation.

For each configuration 5 scenarios will be analyzed, considering the different types of structure assessed (steel, steel 60 years, wood, wood with replacement and wood with coating).

Sub-section 1: opaque PV, distant trackers

As mentioned, the first part of the plant consists of 5 trackers. It considers the use of opaque PV panels (the LEO 400-415 W Premium model), that generate more electricity, and the installation of the trackers further from each other's (5.9 m distance). The peak power of 1 module is 400 Wp; therefore, the total installed power of this part of the configuration is 30 kWp (6 kWp per tracker).

The total lifetime expected for the plant is 30 years, and it will be located in the region of Baix Llobregat (close to Barcelona). An evaluation through the PVGIS tool allows to estimate the annual electricity generation of the plant, that is 46'979.9 kWh/year, for a total generation of 1'409 MWh along its lifetime. This is the value used to evaluate the impact on the assessed environmental indicators of 1 kWh generated (functional unit 4). The results are evaluated for the 5 structure scenarios described in the previous chapters: the steel structure ("steel"), the steel structure where the elements are reused for a total of 60 years ("steel 60"), the structure partially made of wood without replacement of the components ("wood"), the structure partially made of wood and replaced after 15 years ("wood 15y") and the one where the wood components are covered with a protective coating, applied every 7-8 years ("wood coat").

Table 1.22. ***SYMBIOSYST configuration, sub-section 1, results***

Impact category	Unit per UF (kWh)	Total with steel structure	Total with steel 60 structure	Total with wood structure	Total with wood 15y structure	Total with wood coating
Climate change	kg CO2 eq	0.0327	0.0312	0.0317	0.0326	0.0320
Ozone depletion	kg CFC11 eq	3.17E-09	3.05E-09	3.10E-09	3.23E-09	3.12E-09
Ionising radiation	kBq U-235 eq	0.0026	0.0024	0.0026	0.0027	0.0026
Photochemical ozone formation	kg NMVOC eq	1.31E-04	1.24E-04	1.28E-04	1.34E-04	1.29E-04
Particulate matter	disease inc.	2.66E-09	2.52E-09	2.76E-09	3.05E-09	2.77E-09
Human toxicity, non-cancer	CTUh	2.04E-09	1.64E-09	1.62E-09	1.66E-09	1.63E-09
Human toxicity, cancer	CTUh	7.21E-11	5.45E-11	5.41E-11	5.66E-11	5.46E-11
Acidification	mol H+ eq	2.03E-04	1.94E-04	2.01E-04	2.09E-04	2.04E-04
Eutrophication, freshwater	kg P eq	1.73E-05	1.61E-05	1.65E-05	1.70E-05	1.66E-05
Eutrophication, marine	kg N eq	3.81E-05	3.62E-05	3.77E-05	3.97E-05	3.81E-05
Eutrophication, terrestrial	mol N eq	3.82E-04	3.60E-04	3.78E-04	4.01E-04	3.81E-04
Ecotoxicity, freshwater	CTUe	1.3923	1.2939	1.3514	1.4014	1.3577
Land use	Pt	0.1305	0.1223	0.6037	1.0883	0.6093
Water use	m3 depriv.	0.0285	0.0278	0.0283	0.0288	0.0285
Resource use, fossils	MJ	0.3927	0.3726	0.3808	0.3951	0.3837
Resource use, minerals and metals	kg Sb eq	1.46E-05	9.01E-06	1.13E-05	1.14E-05	1.13E-05

Overall, it can be noticed that the impacts for the wood and steel scenarios are not significantly different. For most of the indicators observed, the wood scenario impacts are between 1% and 5% lower than the ones of steel scenario. The main differences can be observed for the resource use, minerals and metals indicator, where the wood presents lower impacts (around 22% less than the steel scenario), and the human toxicity, cancer and non-cancer (-25% and -21% respectively). On the other hand, the particulate matter in the case of wood scenario is slightly higher than in the steel one (+4%), as already noticed in the previous partial results presented. When considering the other two wood scenarios, the relative impacts compared to the steel one increase. They grow of a few percental points in the case of wood coat scenario, where results often equal the steel scenario ones (and still, the impacts are lower in the case of the 3 indicators formerly mentioned, while higher in the case of particulate matter). For the wood 15 years scenario, namely the one where the structure

wood elements are to be replaced after half of the lifetime, the impacts follow the same pattern but are even higher, almost always slightly exceeding the ones of the steel scenario.

Another aspect to be commented is that, in case the steel composing the structure is re-used for the same application for another 30 years period (steel 60 scenario), the impacts of the steel structure significantly decrease. In fact, in this case the values plummet below the ones presented for all the wood scenarios, making the use of wood elements not convenient from this point of view.

It is important to highlight that the values between the different scenarios are not as different as they were in the case of results for the single elements (structure, PV panels), since the different in this case is due to the different structure types, but the relative weight of structure on the total impacts is limited if compared to the one of the PV panels (as will be commented successively).

The considerations presented can be observed in the diagram below, where the 5 scenarios are compared in a radar chart, where the reference scenario (set at 100%) is the steel scenario.

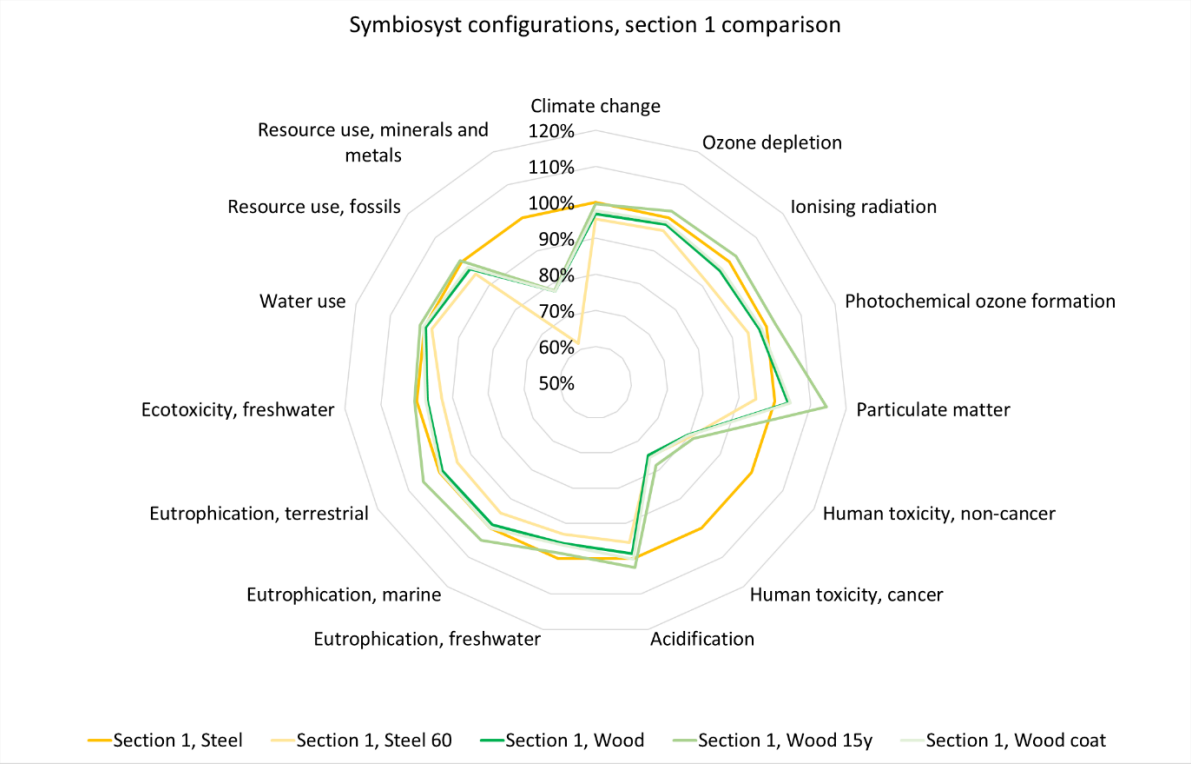


Figure 1.32. Section 1 comparison, SYMBIOSYST configuration

As in the previous sections, the land use indicator is treated separately since its behavior is different. In the figure below the impacts obtained for this indicator are presented per kWh, namely the functional unit 4. As already observed in the separated results, the impact on land use in the case of structure made with wood elements is higher than the case with only steel elements. This increase is mainly due to the use of wood; therefore, the wood coat scenario, where the wood elements are painted with a protective coating, is similar

to the one of simple wood from this point of view. The main difference is in the wood 15y scenario, where the wood components are replaced after half of the lifetime.

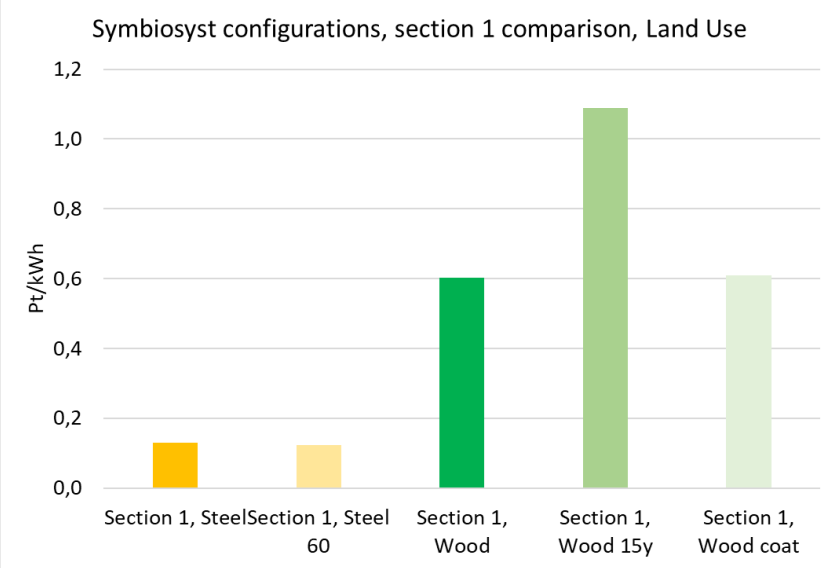


Figure 1.33. SYMBIOSYST configurations, section 1 comparson, Land Use

For all the analyzed scenarios, it can be observed that, for most of the indicators under assessment, the PV panels are responsible for the largest part of the impacts. The exception is the resource use, minerals and metals indicator for which the steel structure represents over 75% of the total impact. In the scenarios using wood to partially compose the poles, the relative weight of the structure on this indicator decreases, since steel, that is responsible for this impact, is used in reduced amounts. Also in the case of human toxicity (both cancer and non-cancer) the relative impact of the wood structure cases is significantly lower than in the case of wood structures.

The opposite trend occurs for the land use indicator: in the scenarios using wood for the structure, the relative impact of the structure on this indicator is significantly higher than in the steel case, since wood has a noticeable impact on the indicator.

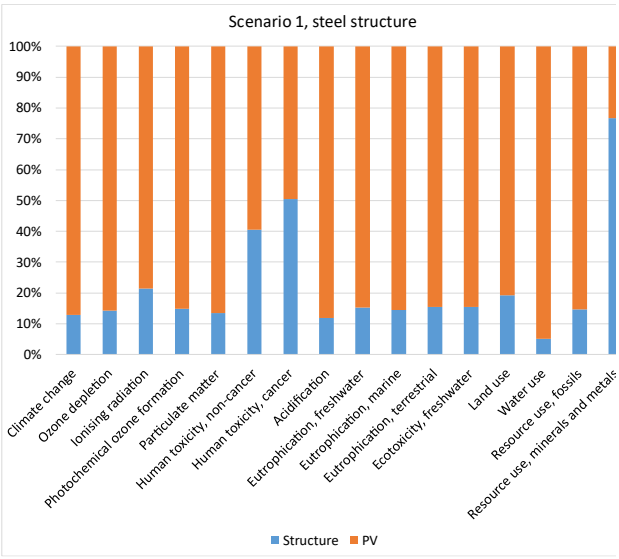


Figure 1.34. SYMBIOSYST configuration, Scenario 1, Steel structure

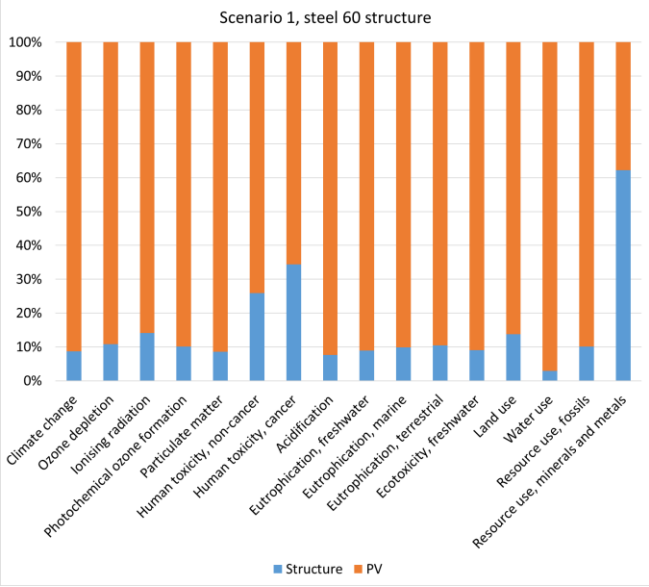


Figure 1.35. SYMBIOSYST configuration, Scenario 1, Steel 60 structure

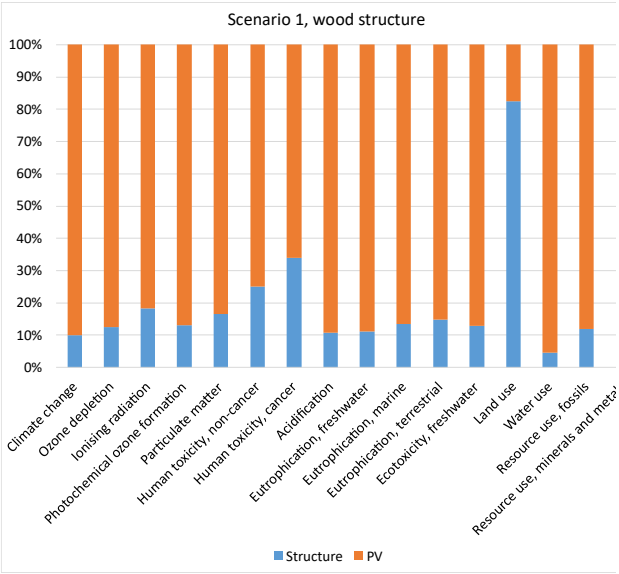


Figure 1.36. SYMBIOSYST configuration, Scenario 1, Wood structure

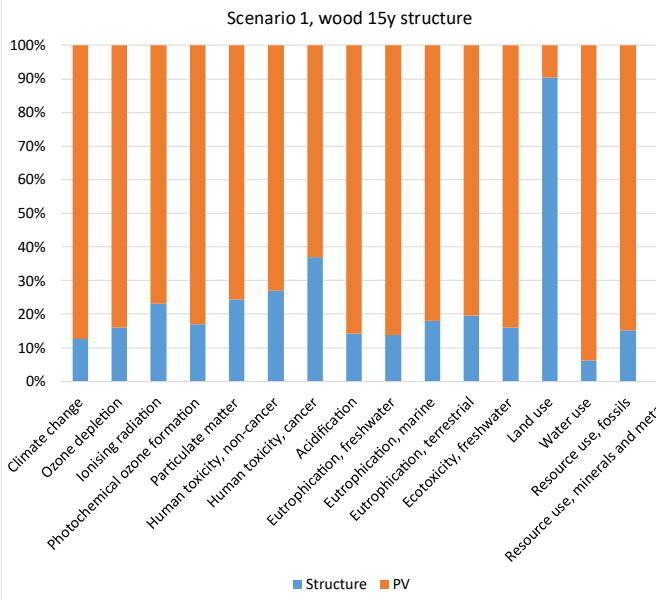


Figure 1.37. SYMBIOSYST configuration, Scenario 1, Wood 15y structure

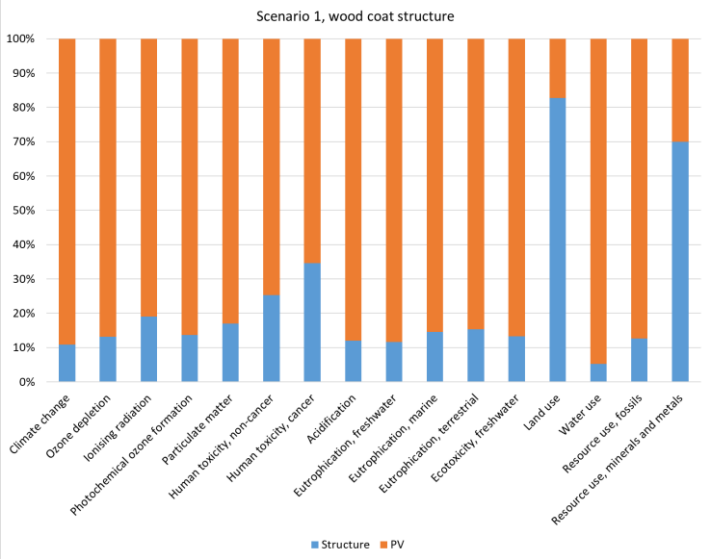


Figure 1.38. SYMBIOSYST configuration, Scenario 1, Wood coat structure

Sub-section 2: semi-trans PV, closer trackers

The other part of the plant consists of 5 trackers as well. It considers the use of PV modules where only a portion is made of opaque cells, around 60% of the module surface, while the remaining part is made of a translucent material that allows light to reach the crops (semi-trans PV). Because of this, the trackers can be placed closer without affecting the crops negatively. It was thus decided to place the trackers at a distance of 4.1 m.

The peak power of 1 module is, in this case, 240 Wp; therefore, the total installed power in 1 tracker is 3.6 kWp, meaning that the total power for this part of the configuration is 18 kWp.

As for the other sub-section the total lifetime expected for the plant is 30 years, and it will be located in the region of Baix Llobregat. The estimation of the annual electricity generation of the plant is 28’188 kWh/year, for a total generation of 845.6 MWh throughout its lifetime. This is the value used to evaluate the impact on the assessed environmental indicators of 1 kWh generated (functional unit 4).

Also in this case, the results are evaluated for the 5 structure scenarios described in the previous chapters: the steel structure (“steel”), the steel structure where the elements are reused for a total of 60 years (“steel 60”), the structure partially made of wood without replacement of the components (“wood”), the structure partially made of wood and replaced after 15 years (“wood 15y”) and the one where the wood components are covered with a protective coating, applied every 7-8 years (“wood coat”).

Table 1.23. SYMBIOSYST configuration, sub-section 2, results

Impact category	Unit per UF (kWh)	Total with steel structure	Total with steel 60 structure	Total with wood structure	Total with wood 15y structure	Total with wood coating
Climate change	kg CO2 eq	0.0431	0.0406	0.0414	0.0429	0.0419
Ozone depletion	kg CFC11 eq	3.92E-09	3.72E-09	3.81E-09	4.03E-09	3.85E-09
Ionising radiation	kBq U-235 eq	0.0034	0.0030	0.0033	0.0035	0.0033
Photochemical ozone formation	kg NMVOC eq	1.74E-04	1.62E-04	1.69E-04	1.79E-04	1.71E-04
Particulate matter	disease inc.	3.85E-09	3.62E-09	4.02E-09	4.50E-09	4.05E-09
Human toxicity, non-cancer	CTUh	3.00E-09	2.32E-09	2.29E-09	2.36E-09	2.30E-09
Human toxicity, cancer	CTUh	1.13E-10	8.39E-11	8.33E-11	8.75E-11	8.41E-11
Acidification	mol H+ eq	2.83E-04	2.67E-04	2.78E-04	2.92E-04	2.83E-04
Eutrophication, freshwater	kg P eq	2.34E-05	2.14E-05	2.21E-05	2.30E-05	2.23E-05
Eutrophication, marine	kg N eq	5.07E-05	4.74E-05	4.99E-05	5.33E-05	5.07E-05
Eutrophication, terrestrial	mol N eq	5.17E-04	4.81E-04	5.12E-04	5.50E-04	5.16E-04
Ecotoxicity, freshwater	CTUe	1.9799	1.8160	1.9117	1.9950	1.9223
Land use	Pt	0.1800	0.1663	0.9686	1.7762	0.9781
Water use	m3 depriv.	0.0322	0.0311	0.0320	0.0328	0.0323
Resource use, fossils	MJ	0.5161	0.4827	0.4964	0.5201	0.5011
Resource use, minerals and metals	kg Sb eq	2.32E-05	1.39E-05	1.78E-05	1.78E-05	1.78E-05

In this case, similar considerations to the ones reported for the section 1 can be made, in terms of comparison of the 5 scenarios between them. In addition, the results of section 2 can be compared with the corresponding ones obtained for section 1. In this case the difference between a scenario and the corresponding one is due to the PV panels, and to the fact that the impacts are allocated to a different amount of electricity generated (60% less electricity per panel in the case of section 2). While the impact of panels will also change in the 2 cases, with the panels of section 2 having lower impacts than the ones in section 1 due to the fact that less cells are used (even though not in a linear way), the structure is expected to be exactly the same in the different section cases. Therefore, as expected, the impacts per kWh (UF 4) of each scenario in section 2 are higher than the ones of the same scenario in section 1. For example, the steel scenario in section 2 presents between 13% and 60% higher impacts than the steel scenario in section 1. The same happens to the other scenarios. A visual summary of what described in this section can be observed in the following diagram, where

the 5 scenarios of section 2 are presented and compared to the base case of steel scenario, section 1 (the same base case as in the diagram presented before, in Figure 1.32).

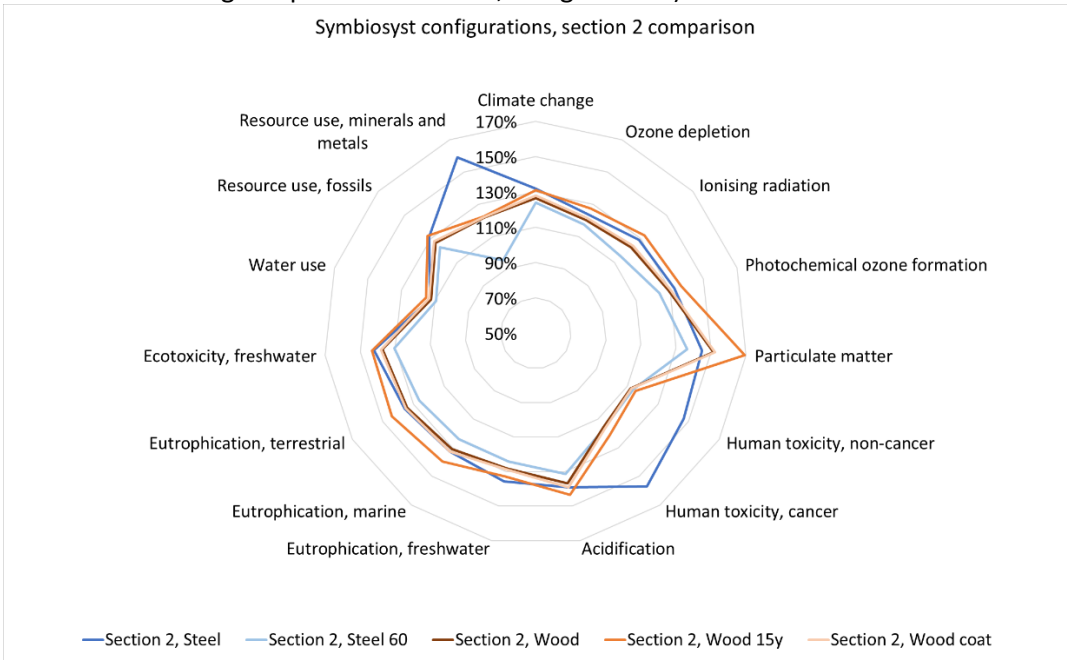


Figure 1.39. ***Section 2 comparison, SYMBIOSYST configuration***

For what concerns the Land Use indicator, the same considerations made for section 1 are applicable. The values obtained for kWh, higher than the ones in section 1 as for the other indicators, are illustrated in the image below.

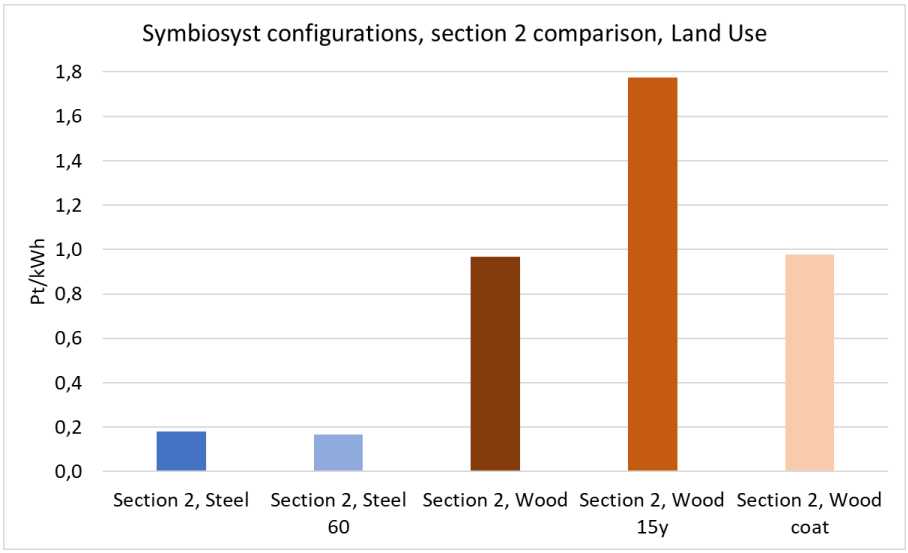


Figure 1.40. ***SYMBIOSYST configurations, section 2 comparson, Land Use***

The diagrams reported in figures 41-45 allow to evaluate the relative impact of the structure and of PV panels on the total for each impact category. Similar considerations as the ones presented for scenario 1 can be made.

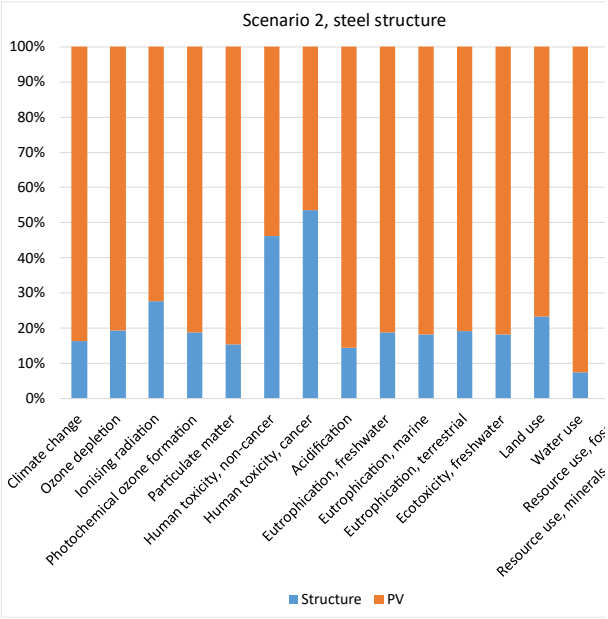


Figure 1.41. SYMBIOSYST configuration, Scenario 2, Steel structure

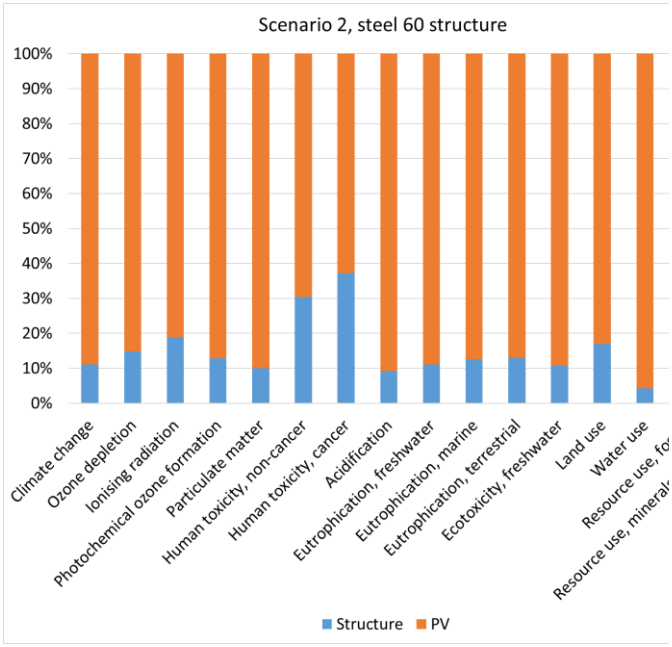


Figure 1.42. SYMBIOSYST configuration, Scenario 2, Steel 60 structure

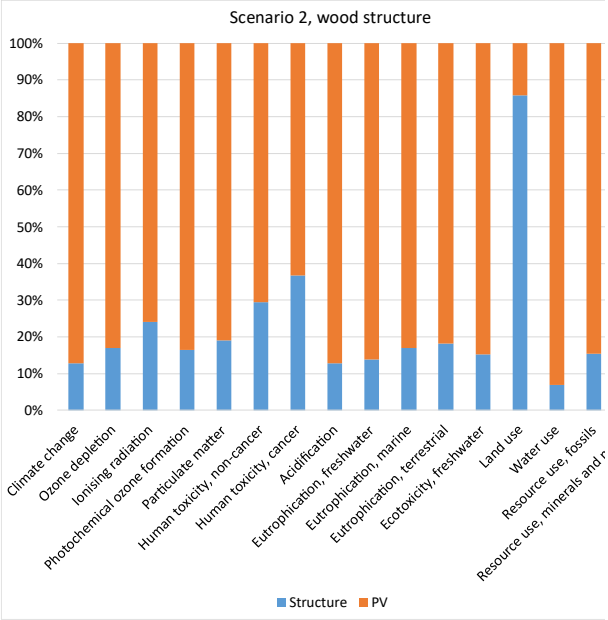


Figure 1.43. SYMBIOSYST configuration, Scenario 2, Wood structure

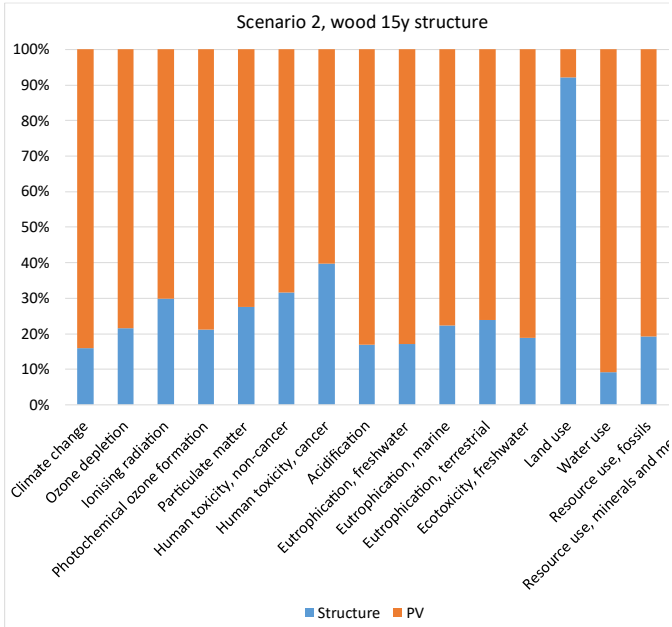


Figure 1.44. SYMBIOSYST configuration, Scenario 2, Wood 15y structure

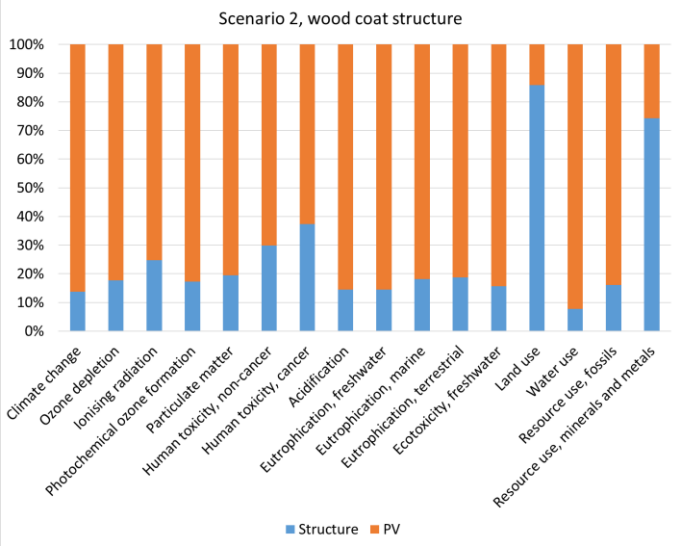


Figure 1.45. SYMBIOSYST configuration, Scenario 2, Wood coat structure

Comparison

In order to provide a visual comparison between the sub-cases analysed, the following radar chart unifies the results obtained. The total values are taken for each scenario (PV+structure), and are referred to the 100% corresponding to the values of the case of the sub-section 1 with the steel structure (as previously made for each sub-section separately). The analysis is presented for all the indicators encompassed excluded the land use one, that is discussed separately.

It can be observed that, as previously mentioned, the values of the sub-section 2, namely the case with the semi-trans PV panels and with the shorter distance between trackers, are higher than the impacts of the other configuration (opaque PV, closer trackers) in most of the impact categories, with the exception of Human toxicity (both cancer and non-cancer indicator). In both cases, for each section the impacts are higher in the scenario with the steel structure than the wood ones, especially in the resource use, minerals and metals indicator where the steel case presents significantly higher impacts. The two wood scenarios of each configuration present similar values, where the wood 15y scenario has slightly higher values than the simple wood and wood with coat ones.

These trends are mainly due to the fact that, as explained, in section 2 the PV panels present less cells, while the structure is the same as in section 1, having the same impact allocated to a lower generation (40% less than in section 1). Although the cells are less than in section 1, other elements composing the PV cells, as cables, glass and other elements, are still needed and their impacts are, once again, allocated to a lower generation.

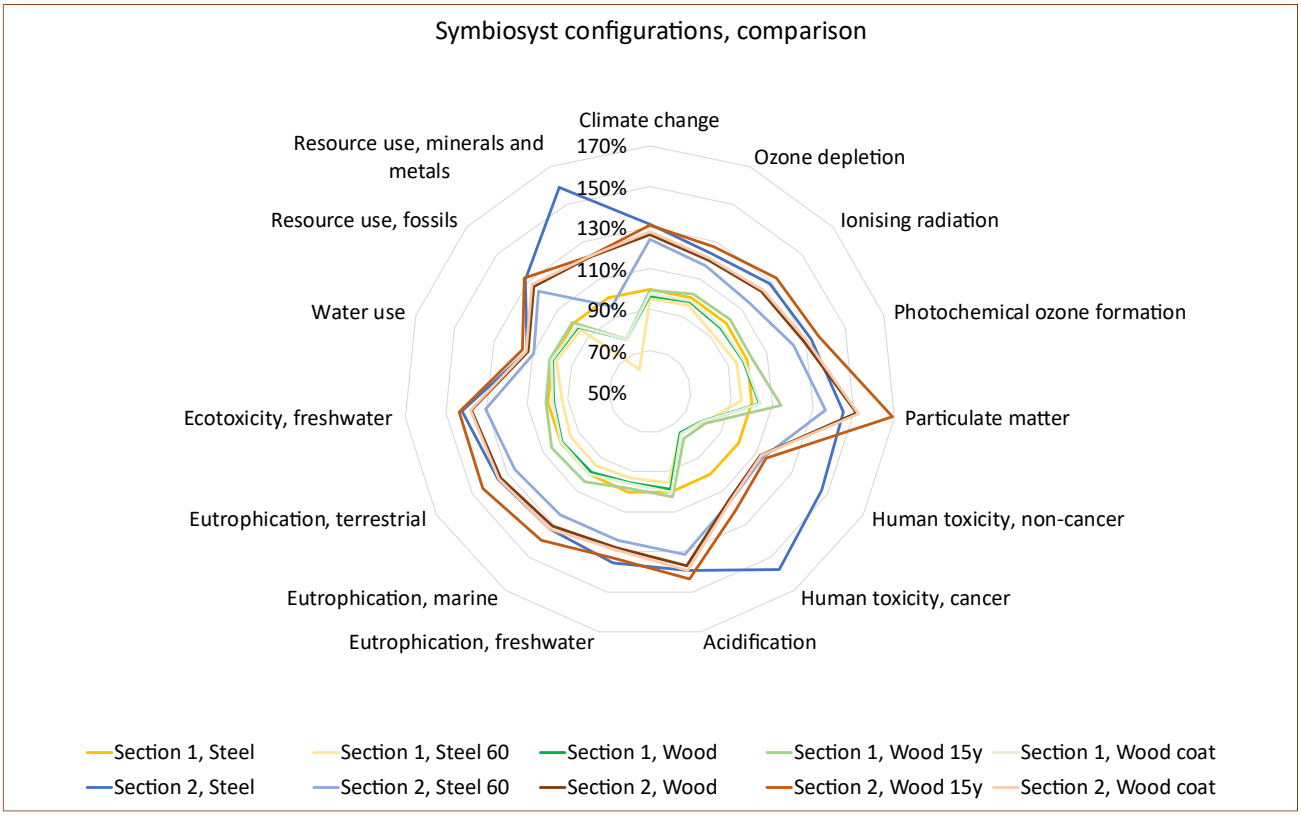


Figure 1.46. SYMBIOSYST configuration, scenarios comparison

A different trend can be observed for the land use indicator, as already pointed out in the previous sections. In this case, the steel scenario is the one presenting the lower impact, while the scenario with the wood replacement has a more important impact (more than double than in the steel scenario in case of replacement after 15 years). This can be explained by the fact that wood is a material that directly affects land use in a more important way than steel. The configuration in sub-section 1, where the opaque PV cells are used, presents slightly higher impacts than the corresponding scenarios in sub-section 2.

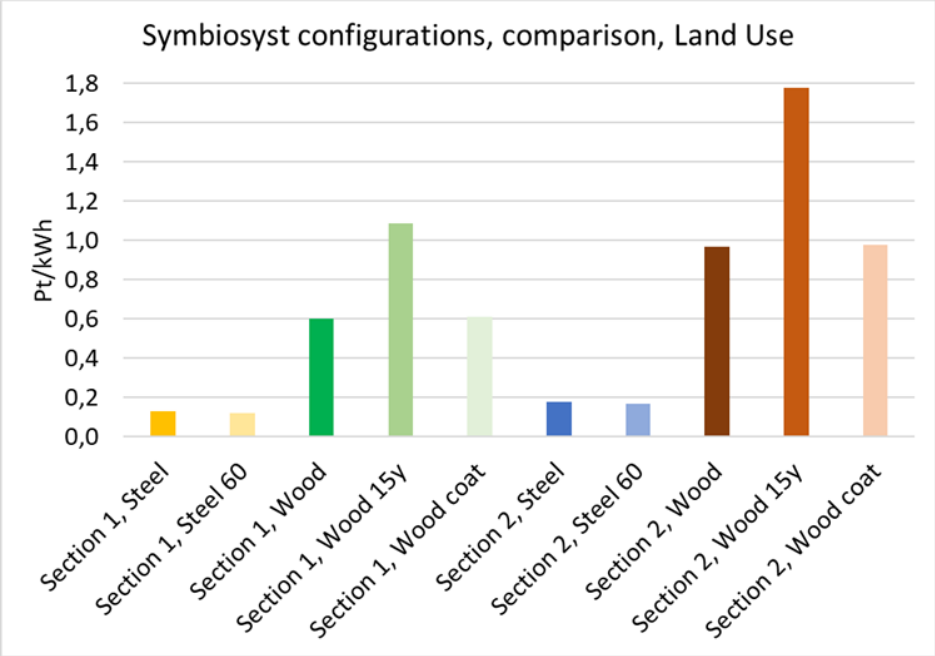


Figure 1.47. SYMBIOSYST configuration, scenarios comparison, Land Use

It can be interesting to have an insight on the Climate Change indicator, that is one of the most important and commented ones. As presented in Figure 1.48, almost all the impacts are due to the PV panels, rather than to the structure. The CO_2e emissions are higher in the case the steel structure is used: the use of the wood structure can allow for a reduction of 3.2% of the total emissions in section 1 and 4.1% in section 2. It can also be observed that, for all scenarios of section 2, the emissions are higher than the worst-case scenario (steel structure) of section 1.

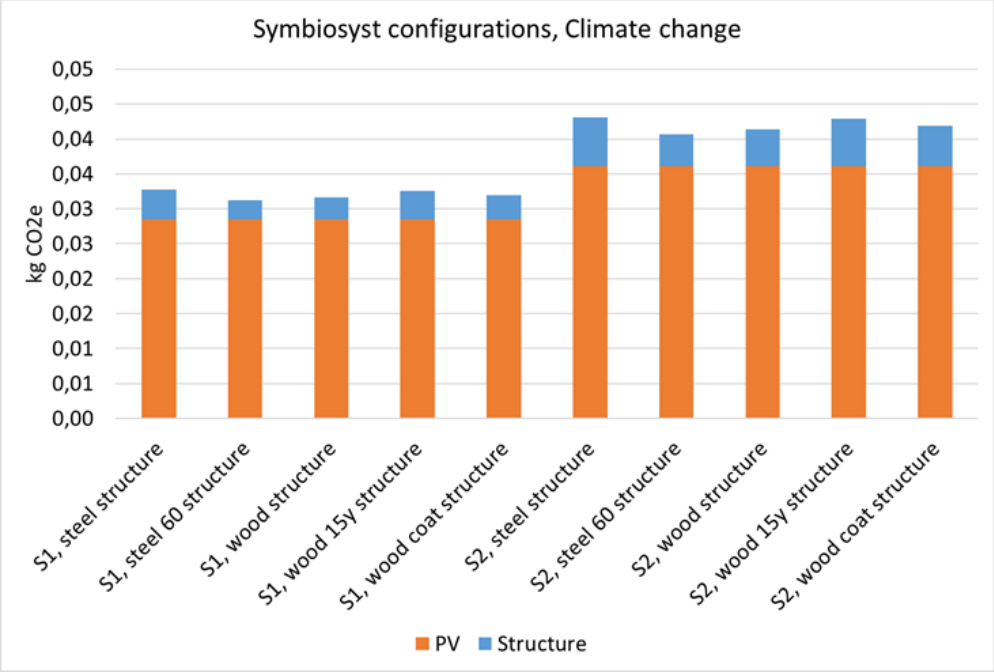


Figure 1.48. SYMBIOSYST configuration, scenario comparison, climate change indicator

1.4.3.2 *HECTARE CONFIGURATION*

The SYMBIOSYST configuration described in the previous section is a pilot. Nevertheless, it is interesting to evaluate the potential application of the analyzed configurations on a larger scale.

Each of the 2 configurations previously analyzed will be taken into account for an application in a 1-hectare field (square field, 100 m x 100 m).

Since the impacts have been evaluated per functional unit, namely per kWh of electricity generated, the results per functional unit are the same obtained for the SYMBIOSYST configuration (section 4.3.1). Hereafter, the configuration details and the electricity generation associated to each of them is presented.

Scenario 1: closer trackers, standard PV

The length of 1 tracker considered in this study is 19.2 m. Considering that the field is square with 100 meters sides, each line of trackers includes 5 trackers.

This scenario is built considering that the distance between trackers lines is 5.9 meters. This corresponds to a total of 16 lines of trackers in the field, as depicted in the picture below (Figure 1.49). The total number of trackers in the field is thus equal to 80. The PV panel selected are the ones described in the base case depicted in section 3.2.1., namely the LEO 400-415 W Premium ones.

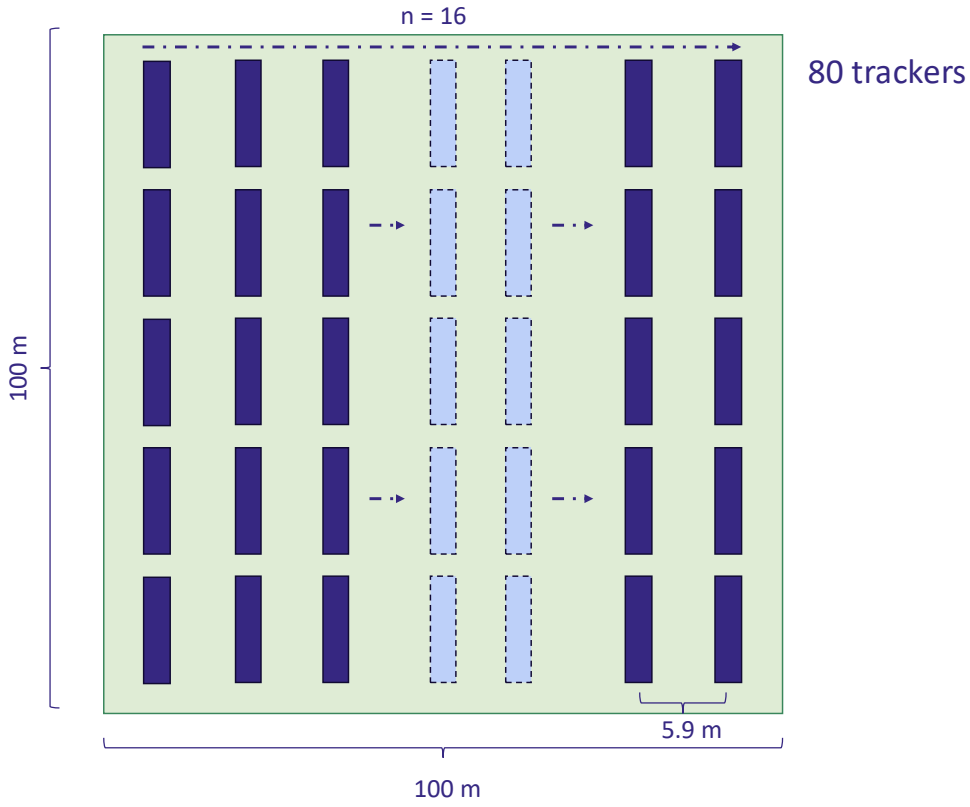


Figure 1.49. ***Hectare configuration, Scenario 1***

The peak power of 1 module is 400 Wp; therefore, the total installed power of this part of the configuration is 720 kWp.

The conditions are the same described in the SYMBIOSYST configuration; therefore, the total lifetime expected for the plant is 30 years, and it will be located in the region of Baix Llobregat (close to Barcelona). Through the PVGIS the total annual electricity generation was estimated to be 751.7 MWh/year, for a total generation of 22'550 MWh along its lifetime. This is the value used to evaluate the impact on the assessed environmental indicators of 1 kWh generated (functional unit 4).

The hectare configuration scenarios are built on the same configuration of the SYMBIOSYST case, with the difference that the hectare configuration is extended to a larger field, namely a hectare, while in the SYMBIOSYST one each scenario is only made of 5 trackers. Nevertheless, the functional unit to which the results are referred is 1 kWh of electricity generated for both cases. As a consequence, all the relative impacts and the comparison between the sub-scenarios presented in the SYMBIOSYST case are exactly the same as in the hectare ones, due to the fact that the elements that compose the plants are the same. Therefore, the considerations are not repeated in this section.

Scenario 2: further trackers, semi-trans PV

The trackers size is the same as in scenario 1 (length of 19.2 meters), and also in this case each line includes 5 trackers.

This scenario is built considering that trackers lines are located with a larger distance than before, namely 4.1 meters. This means that, in total, the field includes 24 lines of trackers. The total number of trackers is thus 120 (Figure 1.50).

In this case, the PV panels used are different from the ones considered before, as described in section 3.2.2. The modules are expected to be composed for around 60% of opaque cells (the common ones, as in scenario 1), while the remaining 40% is made by a translucent material that allows light to reach the crops. Because of this, the amount of electricity generated by 1 module will be lower than the amount generated by an opaque module.

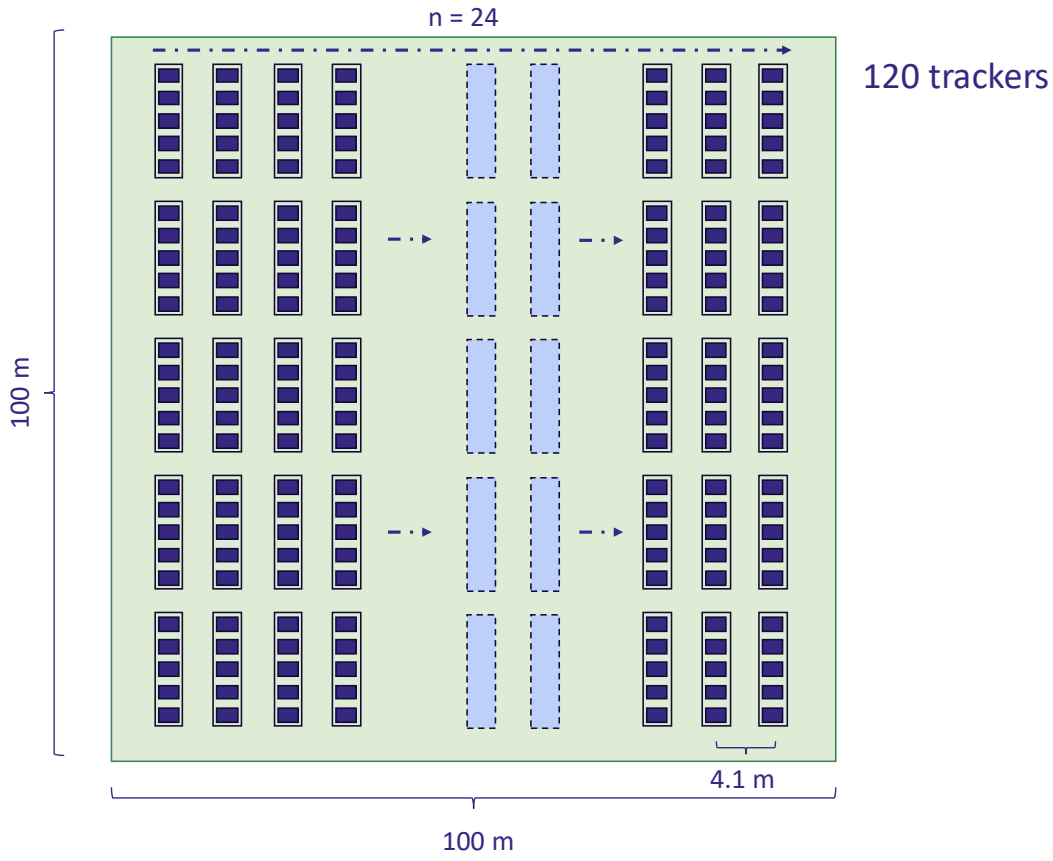


Figure 1.50. Hectare configuration, scenario 2 configuration

In this case, the peak power of 1 module is 240 Wp; therefore, the total installed power of this part of the configuration is 432 kWp.

The total expected electricity generation is estimated to be 676.5 MWh/year, for a total generation of 20’295 MWh throughout its lifetime. As in the previous case, the same relative results obtained for the SYMBIOSYST configuration are valid in this case.

1.4.3.3 *OUTPUT COMPARISON: ELECTRICITY GENERATION*

Another interesting consideration to be made is about electricity generation. In fact, as seen, the different configurations considered (scenario 1 and 2) involve different potential for electricity generation. Since

electricity generation is one of the desired outputs of the project, it is important to assess how the different scenarios assessed would affect this output, beside the different environmental impact that they involve.

In the SYMBIOSYST configuration, the difference is exclusively due to the different types of PV panels used: the base case in scenario 1, and the opaque ones in scenario 2. Consequently, and according to the assumptions made during the definition of the project, the generation in scenario 2 is expected to be around 60% of the one in scenario 1. The yearly generation expected for the two cases is, respectively, of 46'980 kWh/year and 28'188 kWh/year, as depicted in Figure 1.51.

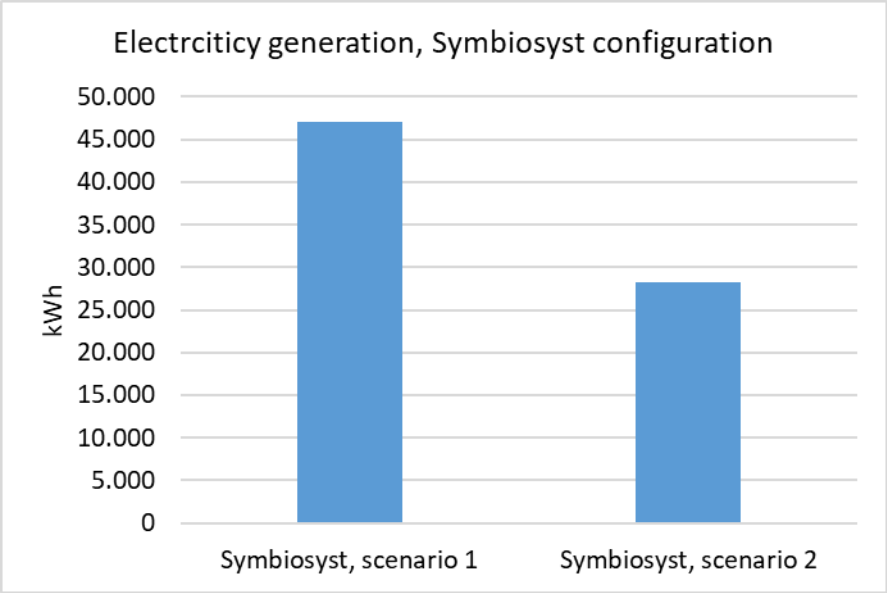


Figure 1.51. Yearly electricity generation, SYMBIOSYST configuration

Taking into account the other configuration studied, namely the one where the two options presented in scenario 1 and scenario 2 are placed in a 1-hectare field, the results are different. In this case, the varying factor is not only the PV panels type, but also the configuration of trackers. In fact, as previously described, in scenario 1 the PV panels present a higher peak power, but trackers are placed further to each other's. Because of this, the installed power between these 2 scenarios is more similar than in the SYMBIOSYST configuration, where space was not a limiting factor. The yearly electricity generation in the scenarios is, with this configuration, 751'678 kWh/year in scenario 1 and 676'510 kWh/year in scenario 2, (representing 90% of the generation in scenario 1). The values are depicted in Figure 1.52.

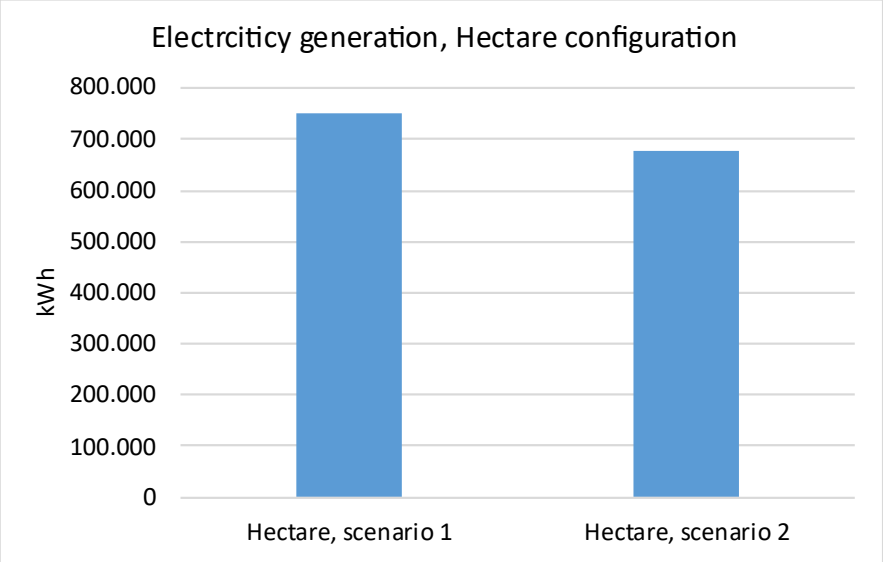


Figure 1.52. Yearly electricity generation, Hectare configuration

It should always remembered that the system analyzed is an agri-PV configuration. Therefore, in addition to electricity generation, the output is the production of agricultural products (crops). This means that, on top of what has already been assessed, the second output has to be considered when evaluating the system's efficiency. This will be made in a more complete way once direct data from the crops grown within the project will be available.

A second aspect that could be interesting to assess in this context is the comparison between the environmental impacts obtained for the electricity generated with the configurations assessed within this project and the impacts that the same amount of electricity would involve if purchased by the national grid. The comparison has been made with the values from the following dataset: "Electricity, low voltage {ES}| market for | Cut-off, S", from the same EcoInvent and SimaPro versions as described before.

The project scenarios analyzed in the comparison, for a better readability of results, are the total results obtained with the steel structure and with the wood structure for scenario 1 and scenario 2. Considering the important different between the project scenarios and the national grid one, it was considered that representing the results of these 4 cases is enough to have a complete view of the results. The impacts related to the generation of 1 kWh (UF 4) of electricity in the 5 mentioned scenarios are presented in Table 1.24.

Table 1.24. Impacts comparison with grid electricity, per functional unit (1 kWh)

		National grid	**Steel, scenario 1**	**Wood, Scenario 1**	**Steel, Scenario 2**	**Wood, Scenario 2**
Climate change	kg CO2 eq	0.3373	0.0327	0.0317	0.0431	0.0414
Ozone depletion	kg CFC11 eq	3.65E-08	3.17E-09	3.10E-09	3.92E-09	3.81E-09
Ionising radiation	kBq U-235 eq	0.2370	0.0026	0.0026	0.0034	0.0033
Photochemical ozone formation	kg NMVOC eq	1.30E-03	1.31E-04	1.28E-04	1.74E-04	1.69E-04
Particulate matter	disease inc.	7.64E-09	2.66E-09	2.76E-09	3.85E-09	4.02E-09

		National grid	Steel, scenario 1	Wood, Scenario 1	Steel, Scenario 2	Wood, Scenario 2
Human toxicity, non-cancer	CTUh	5.10E-09	2.04E-09	1.62E-09	3.00E-09	2.29E-09
Human toxicity, cancer	CTUh	1.57E-10	7.21E-11	5.41E-11	1.13E-10	8.33E-11
Acidification	mol H+ eq	3.00E-03	2.03E-04	2.01E-04	2.83E-04	2.78E-04
Eutrophication, freshwater	kg P eq	1.41E-04	1.73E-05	1.65E-05	2.34E-05	2.21E-05
Eutrophication, marine	kg N eq	4.63E-04	3.81E-05	3.77E-05	5.07E-05	4.99E-05
Eutrophication, terrestrial	mol N eq	4.83E-03	3.82E-04	3.78E-04	5.17E-04	5.12E-04
Ecotoxicity, freshwater	CTUe	6.3301	1.3923	1.3514	1.9799	1.9117
Land use	Pt	1.6998	0.1305	0.6037	0.1800	0.9686
Water use	m3 depriv.	0.2296	0.0285	0.0283	0.0322	0.0320
Resource use, fossils	MJ	7.7407	0.3927	0.3808	0.5161	0.4964
Resource use, minerals and metals	kg Sb eq	2.73E-06	1.46E-05	1.13E-05	2.32E-05	1.78E-05

As can be observed, the electricity generated through the project scenarios presents impacts significantly lower than the one from the national grid for all the indicators assesset (with the exception of "Resource use, minerals and metals". The comparison, where the 100% case is the grid electricity, is illustrated in Figure 1.53.

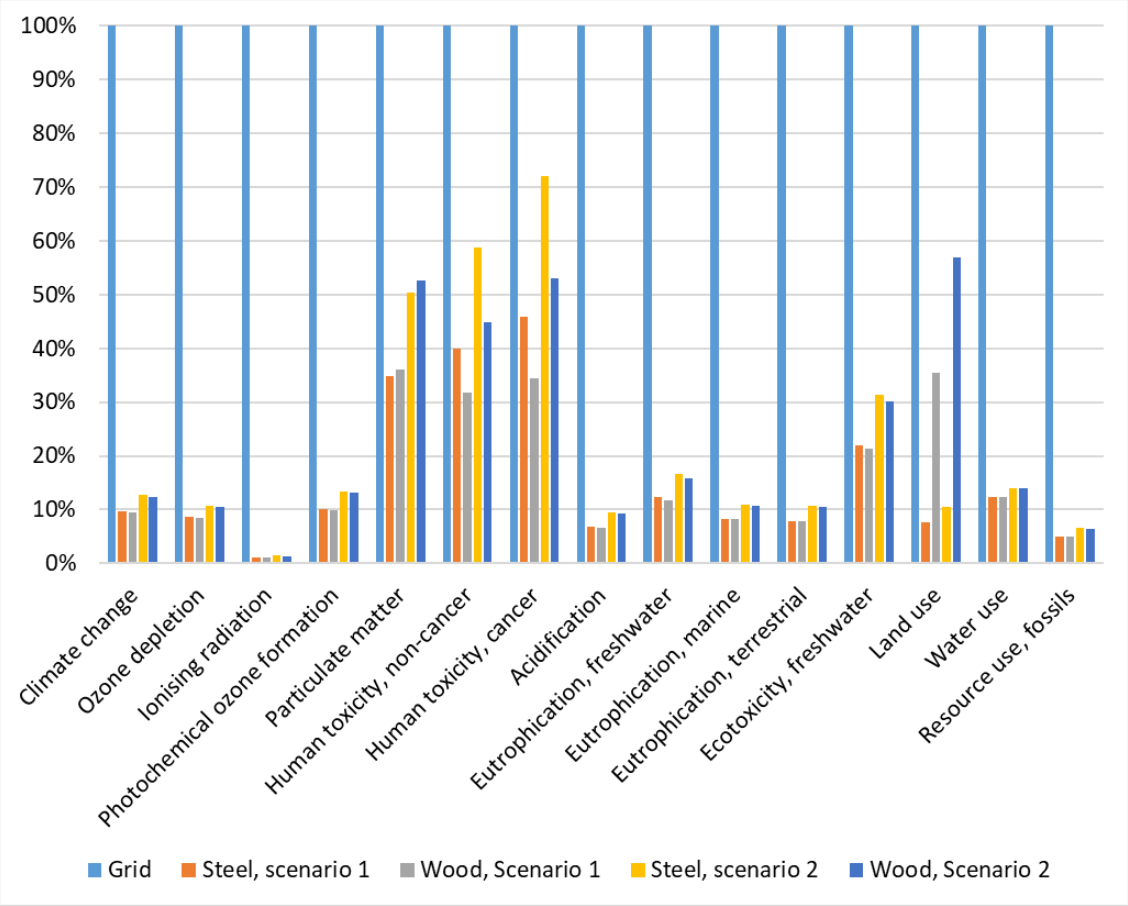


Figure 1.53. Results comparison, with grid electricity (except "Resource use, minerals and metals")

The Resource use, minerals and metals indicator presents opposite results. In fact, as observed in the previous table, the results obtained in the project scenarios involve significantly higher impacts than in the case of grid electricity.

ANNEX 2: HOLISTIC ANALYSIS TO USE WOOD FOR MOUNTING STRUCTURES

One of the objectives of the SYMBIOSYST project is to explore the possibility of incorporating wooden structures as replacements for the traditional steel frameworks used to support photovoltaic panels in the field, with the aim of enhancing the sustainability of the system.

The project includes a decision-making milestone (MS4- Use of wood for mounting structures) where the viability of implementing a wooden structure needs to be determined. This annex aims to conduct a holistic analysis to facilitate a decision on whether to deploy a wooden structure in the SYMBIOSYST pilots. To achieve this, an analysis of the technical requirements for photovoltaic panel structures and market expectations is conducted initially. Subsequently, each aspect is examined, and a comparison is made between the traditional steel framework and a concrete structure.

1.1 TECHNICAL REQUIREMENTS IN AGRI-PV SYSTEMS

In the pursuit of a comprehensive understanding of the potentialities of wood and structural integration within the domain of agri-photovoltaics (Agri-PV), a meticulous examination encompassing pivotal parameters has been undertaken. This analysis, marked by its holistic nature, strives to shed light on the intricacies of employing wood as a structural material while assessing its synergy with existing framework components.

The criteria and parameters considered the analysis have been carefully selected through the expert judgment methodology, an approach that involves the opinions and experience of qualified professionals in the field subject to study. These experts were intentionally chosen from the companies that constitute the collaborative consortium of the project experts in agronomy, agricultural practice and PV installations.

The selection of experts was based on their extensive knowledge and expertise in one of the relevant domains (i.e. agronomy, agricultural practice and PV installations) ensuring that the insights provided were robust and backed by a deep understanding of the critical factors at play. The involvement of these professionals, hailing from diverse consortium partners, brought forth a range of perspectives and approaches, thereby enriching the quality and robustness of the final parameters considered in the study. The selected parameters are:

- **Structural Loads:** A fundamental aspect of the evaluation revolves around the structural loads borne by structure and its compatibility with the dynamic demands posed by Agri-PV systems.

- **Durability:** Durability plays a crucial role in structures, considering both the significant investment and the market's desire for structures to match solar panels' lifespan.

- **Sustainability:** Central to this holistic analysis is a meticulous assessment of the sustainability implications stemming from the adoption of wood and structural integration. The life cycle assessment (LCA) of wood-based components vis-à-vis conventional materials offers insights into potential environmental benefits and limitations, aligning with the project's overarching goals of reducing ecological footprints.

- **Raw Materials Availability:** The feasibility of wood as a structural resource is contingent upon the availability of raw materials. A rigorous evaluation of the sourcing and replenishment of wood resources is conducted to determine the viability of large-scale implementation without detrimental impacts on ecosystems.

- **Cost:** An economic dimension is crucial in any endeavor. Comprehensive cost analyses, accounting for factors such as material acquisition, fabrication, installation, and maintenance, provide a comprehensive understanding of the financial implications associated with incorporating wood and structural integration within Agri-PV systems.

This multi-faceted analysis converges to offer a holistic perspective on the potentialities, challenges, and benefits of adopting a wood and structural integration approach within Agri-PV installations. Through a meticulous examination of these critical parameters, SYMBIOSYST aims to unveil a more sustainable, durable, and efficient pathway toward advancing agri-photovoltaic technology.

1.2 ANALYSIS OF EXISTING WOOD SOLUTIONS IN AGRICULTURE

1.2.1 WOOD USAGE IN AGRICULUTRE

The utilization of wooden structures in agriculture is far from an uncommon practice; rather, it stands as a well-established technique that bears manifold advantages across various facets of agricultural pursuits. The versatility, durability, and eco-friendliness of wood render it a prized resource, finding its application in a plethora of contexts within this field.

1.2.1.1 *WOOD FOR ESPALIERS*

Primarily, the deployment of wooden structures to provide support for crops is a widespread occurrence. Posts, beams, and analogous components are often employed to underpin plants that demand vertical growth, including grapevines and climbing plants. This strategic application facilitates organized cultivation, ensuring accessibility for maintenance and harvesting operations. Examples of plants that demand vertical growth and benefit from the support of wooden structures include: grapevines, tomatoes, cucumbers, peas, climbing roses, pole beans or passion fruit. Typically, the posts utilized for this purpose have lengths ranging from 2.5 to 3.5 meters and diameters spanning between 6 to 12 centimetres. In the exceptional context of hop cultivation, posts are notably extended, reaching lengths of 6 to 7 meters and featuring diameters spanning between 10 and 16 centimetres.

In certain agricultural scenarios, the versatility of wooden structures is amplified through their combination with ropes or metal tensioners. This synergy of materials offers a solution to address the specific requirements of particular crops and environmental conditions.

The utilization of ropes in conjunction with wooden structures proves particularly valuable when providing support for climbing or vining plants. By combining wooden posts and beams with sturdy ropes, a system is created that guides the vertical growth of plants in an organized and efficient manner. Ropes act as guides, ensuring that plants remain in position and preventing them from deviating or becoming entangled.

In more demanding cases, metal tensioners are joined with wooden structures to offer additional support and enhanced strength. This combination becomes crucial in situations where climbing plants, such as grapevines,

develop considerable weight due to a profusion of fruits. Metal tensioners provide extra rigidity to prevent structures from yielding under the load and ensure even distribution of weight.

In environments prone to adverse weather conditions like strong winds, the marriage of ropes and metal tensioners further fortifies the stability of wooden structures. This collaboration guarantees that structures remain steadfastly in place, affording necessary protection to crops and minimizing the risk of damage caused by environmental factors.

The fusion of wood with ropes or metal tensioners constitutes an efficient and adaptable strategy in agriculture. This material alliance is employed to optimize the support of climbing plants, manage heavy loads, and bolster the stability of structures, thereby solidifying agriculture's capacity to confront specific challenges and achieve successful yields.

1.2.1.2 *WOOD FOR PROTECTIVE SYSTEMS*

Moreover, the agricultural landscape commonly witnesses the deployment of wood in protective systems. Meshes, nets, and textiles designed to shield crops from pests, birds, and other detriments find their anchor in these wooden structures. This dual-purpose integration ensures effective protection while cultivating a favorable environment conducive to robust plant growth and development.

Within the realm of soil and water conservation, wooden structures play a pivotal role. The erection of wooden terraces and barriers serves to avert soil erosion on inclined terrains, while concurrently regulating water flow. By stemming the loss of fertile soil, these structures endorse sustainable practices that preserve natural resources and foster agricultural longevity.

1.2.1.3 *AUXILIAR FACILITIES*

Beyond these fundamental roles, wood also finds application in the construction of ancillary edifices tailored to agricultural needs, including warehouses and storage structures. The affordability and practicability of wood offer an economical avenue for the establishment of secure spaces wherein harvested produce, tools, and essential agricultural equipment can be safeguarded.

1.2.1.4 *GREENHOUSES*

In select regions, wood assumes a distinctive role in the construction of agricultural greenhouses and tunnels. While these constructs presently cater to a predominantly non-industrial function, their prevalence is on the rise as a means to provide controlled environments for crops and extend the growing season, ultimately contributing to enhanced yield and quality.

1.2.1.5 *SUMMARY*

In summary, the use of wooden structures in agriculture is a common practice. Wood is used for supporting crops, implementing protective measures, preventing erosion, and constructing auxiliary infrastructure.

Some types of crops utilize wooden structures that can be rethought to incorporate solar panels, such as fruit tree espaliers, tree stakes, or supports for vineyards. Table 1.1 summarizes the standard lengths and diameters of wooden structures per usage and category.

Table 1.1. Summary of main LCA impact indicators for mounting structure configuration (Data extracted from Annex 1, Table 19)

Category	Usage	Standard lengths (m)	Standard diameters (cm)
Multipurpose	Posts and pols producer for multiple purposes	1.8-12	5-30
Wood espaliers	Fruit tree espaliers, tree stakes or as vineyard stakes	2.5-3	6-12
	Hope cultivation	6-7	10-16
Wood for crops protective systems	Poles for anti-hail net structures	4.5-5.5	9-16
	Windbreak poles	5-7	10-16

1.2.2 RAW MATERIALS AND TREATMENTS

In the following lines the most common type of wood for structural purposes are presented:

European Silver Fir (Abies alba). The European silver fir is a coniferous wood commonly found in Central Europe. Its light colour and straight grain contribute to its suitability for various structural applications. European silver is used for beams; framing structures such as roofs, walls and floors; Exterior claddings providing aesthetic appeal and protection. Notably, it withstands environmental stressors effectively. Builders use it for structural beams, frames, and cladding due to its resilience and ease of workability. The main production countries for European silver fir are Austria, Germany, Switzerland, and other Alpine regions.

Sweet Chestnut (Castanea sativa). Sweet chestnut is a durable hardwood prevalent in Europe. Its warm tones and attractive grain make it a popular choice for various outdoor applications. Sweet chestnut is known for its durability and resistance to decay. It has a rich, reddish-brown color and a distinctive grain pattern. Builders appreciate its workability and versatility. The principal applications are beams and posts (in timber-framed structures), cladding and furniture and joinery including doors and windows. The main production countries are Spain, France, Italy, and other Mediterranean countries.

Pine Wood. Pine wood, derived from various pine species such as Pinus sylvestris (Scots pine) and Pinus radiata (radiata pine), is widely used in European outdoor construction. Pine wood has a light color, straight grain, and moderate hardness. It is easy to work with, making it a favourite among builders. The main applications are frames, including roof trusses and wall studs, decking and flooring and cladding. The main production countries are Sweden, Finland, Russia, and other cold-climate regions.

European Oak. European oak, represented by species such as Quercus robur (common oak) and Quercus petraea (sessile oak), is a versatile and robust wood used extensively in construction. European oak has a rich, golden-brown colour and a pronounced grain pattern. It is both durable and attractive. The principal applications include beams and columns, flooring and joinery and furniture. Major country producers include France, Germany, and the United Kingdom.

Ipe Wood (Tabebuia spp). Although not native to Europe, ipe is a tropical hardwood renowned for its exceptional durability. Ipe wood has a dark reddish-brown colour, fine texture, and high density. It is resistant to decay, insects, and extreme weather conditions. The main applications include decking and terraces, boardwalks and bridges and exterior cladding. Brazil is the major producer of ipe.

Cedar Wood. Cedar is a genus of coniferous trees in the plant family Pinaceae (subfamily Abietoideae). This kind of wood is native to the mountains of the western Himalayas and the Mediterranean region. Its main characteristics are its lightweight, aromatic wood with natural resistance to decay and insects. Its main applications include cladding and siding, outdoor furniture and saunas and hot tubs. Cedar is sourced from various European countries.

Composite Wood. While not natural wood, composite materials offer practical advantages for outdoor structures. Composite wood is a synthetic blend of recycled materials.

Glulam Wood. Glued laminated timber is a type of composite wood, commonly used for structural applications. It is an engineered wood, made by several layers of dimensional lumber, that are glued together through resistant adhesives. The advantage of this type of wood is in its strength and resistance, for which it is commonly used for buildings and architectural applications. In addition, thanks to its glued nature, it is possible to have components with bigger sizes and lengths; this is especially useful in case in which the poles, beams or elements in general are supposed to be very long. In fact, a simple beam directly obtained from trees cannot have an important length, since it would be depending on the tree size; moreover, the glued technique allows to recover smaller wood parts that, in the case of simple beams, would get lost.

At European level the Regulation (EU) No. 995/2010 of the European Parliament and of the Council, commonly known as the EU Timber Regulation (EUTR), lays down obligations for operators placing timber and timber products on the European market. This regulation prohibits the supply of illegally harvested timber or timber products in the EU market. Operators cannot place on the market wood that violates the applicable legislation in the country of harvest. Moreover, operators must establish a due diligence system. This involves risk assessment to ensure that only legally harvested timber is traded. The regulation has been in force in the EU since March 2013 and also applies in the European Economic Area (EEA), including Iceland, Liechtenstein, and Norway.

At structural level in the European union the relevant standards are:

- **EN 338:2016 - Structural Timber. Strength Classes.** The purpose of this standard is to define the strength classes for timber. It categorizes wood based on its mechanical properties, such as bending or tension strength. The timber used for structural purposes must carry the CE marking, indicating its strength class according to EN 338. This ensures compliance with necessary strength requirements for structural use.
- **EN 14081-1:2019+A1 - Timber Structures.** Strength-graded Structural Timber with Rectangular Cross Section. The purpose of this standard is to address the structural timber with rectangular cross-sections. It provides general requirements for structural timber, including strength. EN 14081-1 harmonized standard demands CE marking and a DoP. The DoP describes essential characteristics related to strength, as per this standard.
- **EN 1912 - Structural Timber - Strength classes - Assignment of visual grades and species.** The purpose of EN 1912 is to establish a relationship between visual strength grades, species, and sources of timber. It specifies the strength classes defined in EN 338 to which timber can be assigned. EN 1912

helps ensure consistent grading practices across Europe, aiding in quality control and safety in timber construction.

- **EN 384:2016+A1 - Structural Timber. Determination of Characteristic Values of Mechanical Properties and Density.** Its purpose is to provide a method to determine characteristic values of mechanical properties and density for specific populations of sawn timber classified by visual or machine strength grading. It covers sampling, testing, analysis, and data presentation.

Regarding the durability and wood treatment, the main standards are:

- **EN 335:2013 - Durability of wood and wood-based products - Use classes: definitions, application to solid wood and wood-based products.** This Standard defines use classes based on wood and wood-based product exposure. It establishes criteria for evaluating durability under different environmental and usage conditions.
- **EN 350:2016 - Durability of wood and wood-based products - Testing and classification of the durability to biological agents of wood and wood-based materials.** This Standard focuses on the durability of wood and wood-based products. It provides tests and classification for resistance to biological agents in wood and its derivatives.
- **EN 351 Durability of wood and wood-based products.** This standard deals with the natural durability of solid wood and provides guidance for testing and classifying wood's natural durability.
- **EN 460: 2023 - Durability of wood and wood-based products - Guidance on performance.** This Standard offers guidance on selecting wood and wood-based products for situations where they may be subject to degradation by fungi, wood-destroying insects, or marine borers.
- **EN 599 - Durability of wood and wood-based products. - This standard specifies biological tests for wood preservatives based on use class.** It covers preventive treatment of solid timber against wood-attacking fungi, insects, and marine borers.

1.3 STRUCTURAL LOADS

In order to evaluate the structural needs of the components of the system, an analysis of the loads has been performed.

The panels to be hold by the structure are 15 per tracker. The structure of the tracker is slightly different in the case of steel and wood case.

The scheme is, in the two cases, as in the following images.

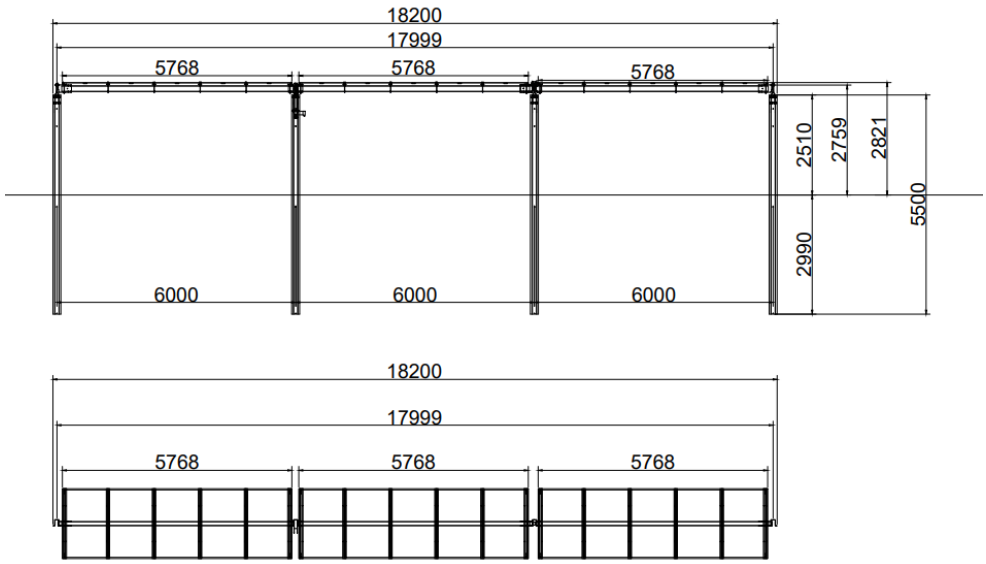


Figure 1.1. Agri-PV scheme steel structure

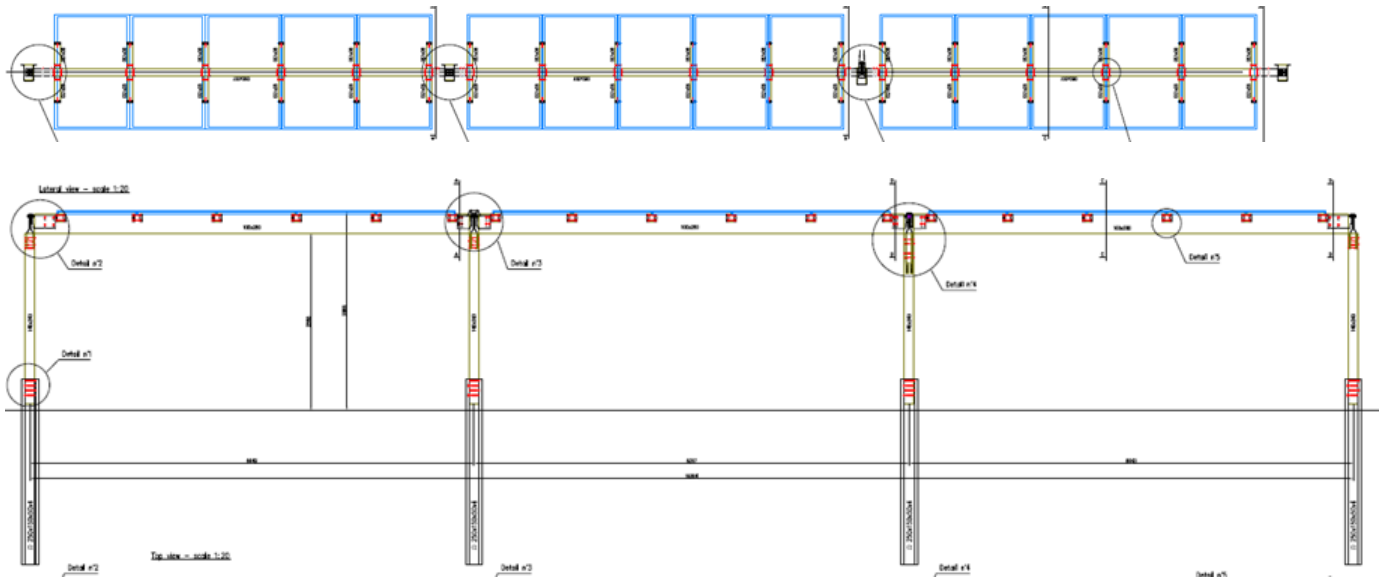


Figure 1.2. Agri-PV scheme, wood structure

The proposed structure, in both cases, have to ensure that the structural loads can be held. A specific analysis has been performed to ensure that the structure is resistant to both loads and deformations. In fact, the load assessment is crucial to evaluate if the system is resistant to the stresses it is subject to. On the other hand, some of the stresses cause deformations in the structure; the system has to make sure it does not variate its shape significantly, if not, the panels could bread (especially the glass components).

The stresses considered are the ones due to the weight of the elements composing the system, the ones related to thermal expansion, and due to wind, snow, and seismic events. All these were evaluated according

to the area in which the system is expected to be installed, namely the area of Barcelona, also in accordance with the codes defined at the European level.

The assessment confirmed that the proposed structures are suitable for this application. The technical details will be fully presented in the complete structural study document, that will be realized and delivered within the scope of the project.

1.4 DURABILITY

1.4.1 MARKET REQUIREMENTS

When we talk about durability, we're talking about different types of durability: technical, visual, financial, etc.

Technical durability refers to the resistance of our material to the constraints we impose on it. In the context of our agri-voltaic structure, the material is subject to several types of stress. Firstly, there is the physical stress due to the weight of the panels. Then there are the stresses associated with the farming activities that will take place under the panels and between the wooden or steel beams. Finally, there are the meteorological constraints specific to the location of the site. For the study phase, we will be based in Barcelona.

We won't dwell on the physical constraints. In fact, the structural studies and the strength of the materials are sufficient to conclude that this will not be a limiting factor throughout the duration of our study (30 years).

With regard to constraints linked to agricultural activity, we must highlight the following points:

- Agriculture, and in particular the cultivation of lettuce, onions, tomatoes and faba, uses large quantities of water, which provides constant humidity. We would like to carry out an in-depth study of moisture storage within our structure. However, at first glance, we can see that the structure will be fairly open on both sides to allow constant circulation and renewal of the surrounding air.
- Growing crops brings with it a whole ecosystem of insects, rodents and other animals. The wood is treated by autoclave for class 4 use, to combat insects and fungi. However, we are never safe from a horde of wild boar destroying a beam. The risk is very small, but it cannot be zero and must be taken into account in the holistic study.

Finally, as far as meteorological constraints are concerned, we can observe several phenomena: Firstly, we should point out that the study is based in Barcelona, where the climate is Mediterranean. This implies, as we can see from the climate data from the National Oceanic and Atmospheric Administration, high temperatures throughout the year and very little precipitation. Added to this is the fact that Barcelona is a coastal city, so there is a slight permanent breeze that allows the air to circulate within the structure, averaging between 8 and 17 kmh throughout the year. This maritime air is also reflected in the region's constant humidity levels. According to Weatherspark, the heaviest period of the year lasts 3.6 months, from 14 June to 2 October, with a heavy, oppressive or stifling feeling at least 15% of the time. The month with the heaviest days in Barcelona is August, with 17.5 or more heavy days. This humid climate during the summer can have an impact on the durability of our wooden beams which can develop fungi easily.

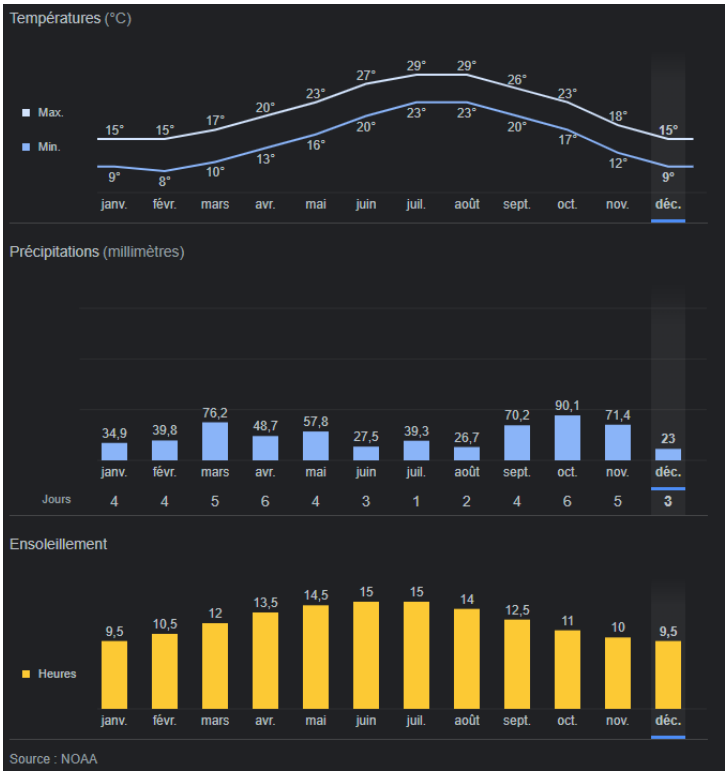


Figure 1.3. Meteorological data from Barcelona

1.4.2 STEEL STRUCTURES

1.4.2.1 *TECHNICAL DURABILITY*

Table 1.2. Technical durability risks for wood

Physical stress	Description
Agricultural stress	Nothing to report
Meteorological constraints	Nothing to report

1.4.2.2 *VISUAL DURABILITY*

The use of galvanised steel means that there has been virtually no degradation of the steel over the 30 years of our study. The visual degradation of the steel will therefore also be very low, and galvanised steel or aluminium and stainless steel should not change colour or rust over the 30 years. The only visible risk that may exist could be tagging.

1.4.3 WOOD STRCUTURES

1.4.3.1 *TECHNICAL DURABILITY*

Table 1.3. Technical durability risks for wood

Physical stress	Description

Agricultural stress	Risks due to the huge amount of water needed to crop lettuce, tomatoes, onions, faba
Meteorological constraints	Risk due to the high temperatures in summer combined with an important humidity

In this case, specific information on how the wood components behave in the long-term, especially for being in contact with the crops and because of the meteorological conditions to which they are subject. In order to get more specific and direct insights on these aspects, further analysis in collaboration with experts working in the structural wood industry could be enriching.

1.4.3.2 *VISUAL DURABILITY*

Wood can become grey with the time. With the replacement of some beams during the 30 years, we will assist to a declination of grey for the beams, that show its age.

1.5 SUSTAINAIBILITY

1.5.1 GOAL AND SCOPE DEFINITION

1.5.1.1 *GOAL DEFINITION*

In 2023, 80% of Spanish harvests were wiped out by the April drought. In addition to water resources, which will be increasingly difficult to control over the next few years, crops will need to be protected from the difficult weather conditions.

As part of the European SYMBIOSYST project, which aims to connect agriculture with solar energy, we're looking for the structure material best suited to our project. Yield is very important, but it is also important to look for an agri-PV structure with a low environmental impact, with minimal disruption to the landscape.

Steel is a safe bet, 100% recyclable but with a high environmental cost. Today, demand for recycled steel exceeds supply. Wood was therefore chosen as an alternative to steel. The poles supporting the structure and the beams holding the PV panels can be replaced by wooden elements, whose mechanical strength is comparable to the steel one.

The goal of the present study is to compare the steel and the partially wooden structures, in terms of environmental impacts on 16 indicators, listed successively. The wood selected for the analysis is the glulam wood, as previously described, due to its higher resistance and suitability to this application.

1.5.1.2 *LCA CONTRIBUTION*

The Life Cycle Assessment, or LCA, is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. In other words, an LCA study evaluates the environmental impact of a product system, according to some modelling choices and assumptions introduced to describe it. The impact is evaluated on specific environmental indicators, that are thoroughly selected according to the project interest. Each indicator assesses a different type of environmental impact and potential damage; that's why an LCA assessment allows for a more complete evaluation of the actual impacts of a product, that can be different and, in some cases, contrasting depending on the indicator analysed.

The process of performing an LCA analysis is standardized in two main ISO standards, recognized at the international level as the reference documents for this type of assessment: the ISO standard 14040:2006/2020 (Environmental management, Life cycle assessment, Principles and framework), that frames a common methodology to be followed when performing an LCA analysis, and the ISO standard 14044:2006/2020 (Environmental management - Life cycle assessment - Requirements and guidelines), that complements it by describing in more detail such approach, also defining specific requirements. Following these standards ensures to follow an agreed methodology, allowing for more comparable results.

By comparing these 2 structures, we set ourselves a simple objective: to find out whether it is holistically interesting to consider a structure partially made of wood rather than one entirely made of steel. The analysis will consider several aspects, such as the availability of the resource, the resistance of each material used and the environmental cost of retrieving them. This will complement the analysis performed to evaluate the feasibility of a partially wooden agri-PV structure compared to a steel one.

1.5.1.3 *TARGET AND AUDIENCES*

The LCA performed is primarily intended to increase the information available on the agri-PV configurations, especially aimed at future agricultural investors and local authorities. In a second phase, this study is also aimed at reaching private citizens. To reach a wide audience, it is important to produce a study whose results are comprehensible to the majority, using simple and clear concepts and diagrams.

1.5.1.4 *SCOPE DEFINITION*

In an LCA study it is crucial to clearly define the boundaries of the systems analysed. In this case, the complete agri-PV plant is depicted in Figure 1.4. This part of the analysis focuses on the structure, as shown by the red dashed line. In this sense, the study compares two potential options, namely a structure made of galvanized steel or another version where some of the steel components are replaced by wood-made components.

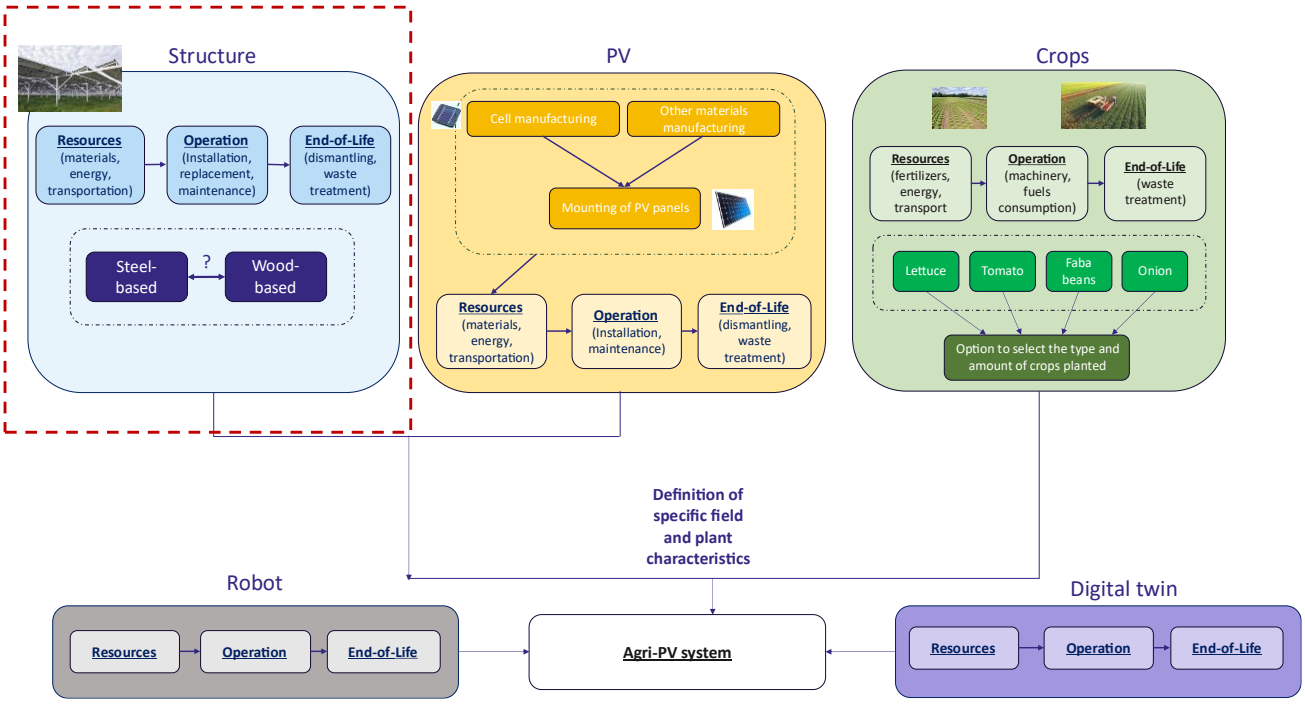


Figure 1.4. System boundaries

The project life of the system is assumed to be 30 years.

More specifically, this part of the study only focusses on the agri-PV structure. The other parts of the whole systems are assessed separately in another part of the study.

Therefore, the present analysis aims at analysing the possibility to replace two steel elements with wood ones:

- **Part of the holding poles.** In this case, not all the element is considered to be replaced. The lower part of the foundations, that is in direct contact with the ground and the materials and water use to grow the crops, is expected to remain made of steel. The upper part of the poles is instead replaced with wood poles, treated in order to be more resistant to atmospheric agents.
- **Beams holding the panels.** The beams that hold the panels in the upper part of the structure are fully replaced with treated wood beams.

For the wood case, three different scenarios are defined. In the first case, it is assumed that the wood elements can resist throughout the whole 30-year-period. Another case, more conservative, is included to assess the case in which the wood parts need to be replaced after 15 years. In addition, a scenario has been evaluated considering that a protective paint coating is used to increase the durability of wood; this coating, refreshed every 7 years, allows the wood to resist throughout the 30 years.

The other elements are expected to remain the same in the two cases, because of structural reasons.

The lifecycle stage included in the present assessment are presented in

Product stage			Construction stage		Use stage							End of life				Benefit and loads			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw material extraction	Transport	Manufacturing in factory	Transport to site	Installation and Erected process	Use	Maintenance	Repair	Replacement	Refurbishment	Operation energy use	Operation water use	Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Landfill
X	X	X	X	X		X	X	X				X	X	X	X			X	X

Figure 1.5. Life cycle stages included

1.5.1.5 *FUNCTIONAL UNIT (FU)*

We also need to define a common functional unit to enable the comparison between the two final structure. Accordingly, 1 tracker able to hold 15 PV panels “leo 400-415W”, for a total of 6 kWp installed power, has been used as the functional unit 1 (FU1) for the systematic comparison of the structural part.
It should be noted that the full configuration is made of 10 trackers.

1.5.1.6 *LIFE CYCLE INVENTORY (LCI)*

An LCA study is based on a crucial stage, called Life Cycle Inventory (LCI). This process consists in the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system. The data elaborated are thus related to the specific system characteristics and to the selected functional unit.

The LCI data of the present analysis includes metal screws and beams fabrication, wooden beams treatment by autoclave, 30 years of operation, transportation, energy consumption, end-of-life dismantling, landfilling and waste treatment.

The life cycle inventory (LCI) data of the steel structure includes metal screws and beams fabrication, 30 years of operation, transportation, energy consumption, end-of-life dismantling and waste treatment.

Regarding the wood used, a construction wood, namely the glued laminated timber (also called glulam in the report) locally retrieved and treated by autoclave. Two French companies specialized in autoclave-treated wood for class 4 use (Querandeau and SIRA) were contacted. The second one is the historical provider of France Télécom and EDF for electricity and telecom poles.

Autoclave-treated wood comes with a 15-year guarantee. These wooden posts are treated so that they can be planted directly in the ground, but this is not the case in this study. The posts will be fixed to metal supports above the ground. However, the presence of high humidity due to agriculture means that class 4 wood must be used. According to them and the information given by their website (lifespan > 20 years), we can easily expect that the wood is going to last 30 years.
As mentioned before, in order to include a more conservative scenario, an additional analysis is performed considering that the wood elements last 15 year, and after this period they have to be replaced.
Alternatively, another wood scenario was taken into account, in which the wood is covered with a protective painting coat, that is refreshed every 7 years, as suggested for outdoor applications that have to face difficult climate conditions (such as direct sun, humidity, and mediterranean climate). In this case, the wood is expected to last 30 years.
In addition, a fifth scenario has been added, considering that the steel structure has a lifetime longer than the one considered. Therefore, a scenario in which the steel parts (poles and beams) are reused for another similar application, and thus in which their impacts are allocated only partially to the present system, has been evaluated.

The present study's inventory is based on the Ecoinvent 3.6 database, Valmont Solar data, the GoPV Project | SUMMER SCHOOL PV SYSTEMS TECHNOLOGIES AND DESIGN and the study of Muller et al. (2021).

1.5.1.7 *ENVIRONMENTAL IMPACT ASSESSMENT METHODS*

Based on EN 15804 and ISO standards 14040 and 14044, a cradle-to-grave LCA has been performed. This means that the study includes all the lifecycle stages, from the extraction of the materials (cradle) to the waste treatment (grave).

The assessment is realized for two common types of structural materials for an agri-PV structure which are wood and steel. This analysis used the 16 environmental indicators that are recommended by the Product Environmental Footprint, namely a method developed by the European Commission and which guidelines are defined in the "Product Environmental Footprint Category Rules".

According to literature on structures and solar panels, the calculation methods was selected, and consequently the indicators evaluated. Based on the study by Muller et al. (2021) about a comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory, we selected EF 3.0 Method (adapted) as the second impact assessment methodology for this research.

With regards to the end-of-life stage, statistics were analysed to develop realistic forecasts. It should be noted that the end-of-life stage will take place in the future, in 25 years after the installation of the system. To assume how the components and waste will be treated in this timeframe, assumptions based on data provided today by independent entities have been introduced.

According to the reports published by EuRIC, 90 % of the aluminium in the construction and transportation are reused.

According to the report published by the French national institute for the circular economy about the steel, 80 % of stainless steel is recycled and near 100 % of steel from construction is recycled, we consider that 95% is recycled at the end.

According to Galvazinc, an independent French association of experts in hot-dip galvanising, 68% of zinc is recovered after the galvanised steel separation process.

According to the French technologic institute named FCBA, the material recovery rate is 44.5%, with 42% recycling and 2.5% reuse, and the energy recovery rate is 48% (including cement plants). Last but not least 7.5% of construction wood waste is landfilled.

1.5.1.8 *SCENARIOS*

According to what described in the previous sections, the assessment has been performed to compare the environmental impacts of the structure made of steel or of wood.
Four scenarios were thus defined:

- **Scenario 1 - Steel structure:** in this case, it was considered that the PV structure is entirely made of steel.

- **Scenario 2 - Steel 60 years structure:** the structure is the same as in the steel structure, but it is considered that the elements are resistant and last more than the lifetime of the plant, namely 60 years; therefore, they can be used for further applications in the same sector. It is thus assumed that only a portion of their impact is to be allocated to the present system, while the remaining one will be allocated to the following applications.

- **Scenario 3 - Wood structure:** it is considered that some steel components of the components are replaced by components made of galvanized wood. Two main elements are replaced: part of the poles and the beams. Regarding the poles, the replacement is not made on the whole pole; the foundation is expected to be made of steel, and will be in contact with the ground, while the upper part will be made of galvanized wood. At the same time, the beams that hold the PV panels will be replaced with galvanized wood. The wood used for these two types of components is the same. In this scenario, we consider that the wood elements are strong enough to be used during the whole 30 years of lifetime of the structure.

- **Scenario 4 - Wood 15 years structure:** it is a second version of the wood structure scenario. Since the wood is guaranteed to be able to operate for a period of 15 years only, a conservative scenario is developed, considering that the wood poles have to be replaced after 15 years in order to ensure the optimal strength. The components that are expected to be made of wood are the same as in the wood

structure without replacement. The same type of wood and of galvanization is considered to be employed.

- **Scenario 5 - Wood structure, coating:** this is a variation of the wood structure scenario. In this case, in addition to what said, to enhance their durability the wood elements are covered with a coating paint, applied every 7-8 years.

1.5.1.9 *WOOD MODELLING*

The choices made for the wood modelling are crucial in the LCA assessment, to ensure the reliability of results. Initially, the analysis was performed with the pynus silvestrys wood type. This wood is not subject to important treatments and processing, and therefore, it presents low impacts. Successively, it was considered that it was more realistic to take into account a different wood type, more commonly used for this type of applications, namely the glulam, a structural wood that persents better strength, a higher ability to hold the weight of the structure and to face weather conditions over time. This material, being an engineered wood, undergoes specific treatments, including the gluing through adhesives, and therefore its production involves higher impacts than the ones of the simple beams of pinus sylvestrys. Nevertheless, although its higher impacts, the use of this material is more likely than the one of the simple untreated beams, and therefore the analysis was updated with this material. In addition, it should be said that the simple beams length entirely depends on the availability of wood, and thus, on the trees height. On the other side, the glulam beams can be longer an take advantage of all the wood of trees trunk, since the material is then worked.

Hereafter, the table presents the impact of 1 kg of material for each of the two wood types analysed, on the 16 indicators considered. The diagram reported successively compares these impacts in a visula form, considering the relative impacts compared to the glulam case (100%). It can be observed that, in all the impact categories analysed, the impact of the glulam are significantly higher than the ones of the simple pine wood. In any case, it is important to remember that the structural requirements need such type of material to resist and operate, therefore, the glulam is selected.

Table 1.4. Results for 1kg of materials, glulam and pine

Impact category	**Unit**	**Glulam**	**Pine**
Climate change	kg CO^2 eq	0.383	0.043
Ozone depletion	kg CFC11 eq	5.36E-08	8.42E-09
Ionising radiation	kBq U-235 eq	0.0778	0.0033
Photochemical ozone formation	kg NMVOC eq	0.0028	0.0007
Particulate matter	disease inc.	1.47E-07	1.70E-09
Human toxicity, non-cancer	CTUh	1.14E-08	1.34E-09
Human toxicity, cancer	CTUh	1.11E-09	5.53E-11
Acidification	mol H+ eq	0.0031	0.0002
Eutrophication, freshwater	kg P eq	0.0002	0.0000
Eutrophication, marine	kg N eq	0.0009	0.0001
Eutrophication, terrestrial	mol N eq	0.0106	0.0009
Ecotoxicity, freshwater	CTUe	13.79	0.52
Land use	Pt	262.03	114.57
Water use	m^3 depriv.	0.217	0.010

Impact category	Unit	Glulam	Pine
Resource use, fossils	MJ	6.17	0.57
Resource use, minerals and metals	kg Sb eq	8.18E-06	5.03E-07

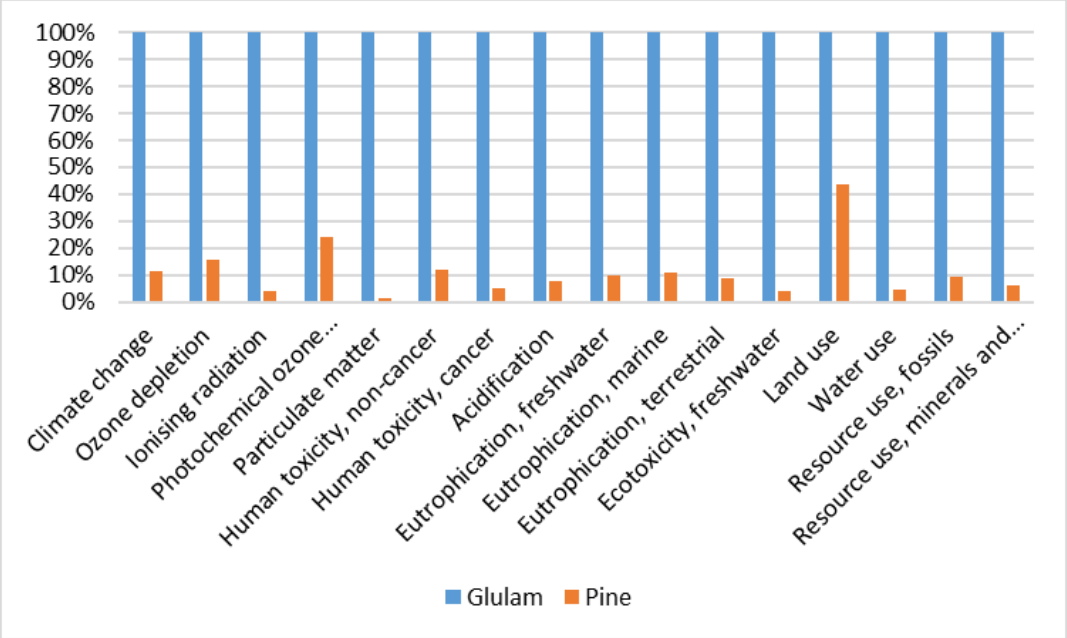


Figure 1.6. Comparison between glulam and pine

1.5.2 RESULTS

This section reports the results obtained for the tree scenarios previously described. The values obtained for each indicator are reported in Table 1.18.

Table 1.5. Results obtained in the 3 scenarios.

Impact category	Unit (per FU)	Steel	Steel 60y	Wood	Wood 15y	Wood, coat
Climate change	kg CO_2 eq	1'189.3	763.1	893.6	1150.1	972.0
Ozone depletion	kg CFC11 eq	1.28E-04	9.32E-05	1.09E-04	1.46E-04	1.15E-04
Ionising radiation	kBq U-235 eq	159.39	96.81	132.26	177.41	137.68
Photochemical ozone formation	kg NMVOC eq	5.52	3.53	4.72	6.44	4.98
Particulate matter	disease inc.	1.00E-04	6.13E-05	1.29E-04	2.09E-04	1.33E-04
Human toxicity, non-cancer	CTUh	2.34E-04	1.19E-04	1.14E-04	1.26E-04	1.16E-04
Human toxicity, cancer	CTUh	1.03E-05	5.28E-06	5.18E-06	5.88E-06	5.32E-06
Acidification	mol H+ eq	6.84	4.19	6.04	8.31	6.91
Eutrophication, freshwater	kg P eq	0.74	0.40	0.52	0.66	0.54
Eutrophication, marine	kg N eq	1.56	1.00	1.44	2.01	1.56
Eutrophication, terrestrial	mol N eq	16.65	10.56	15.74	22.20	16.42

Impact category	Unit (per FU)	Steel	Steel 60y	Wood	Wood 15y	Wood, coat
Ecotoxicity, freshwater	CTUe	60'708	32'975	49'164	63'260	50'959
Land use	Pt	7'088	4'762	140'460	277'051	142'058
Water use	m^3 depriv.	402.62	224.96	368.23	509.30	420.52
Resource use, fossils	MJ	16'213.0	10'556.8	12'867.3	16'890.6	13'677.2
Resource use, minerals and metals	kg Sb eq	3.15	1.58	2.23	2.24	2.23

In order to compare the three scenarios in a visual way, the steel scenario has been taken as the base scenario, namely the reference one. Consequently, for each indicator, all the values were evaluated as percentage values of the base scenario.

The spider diagram in Figure 1.7 and Figure 1.8 show the results obtained for 15 of the 16 indicators encompassed in the study (excluded the Land Use indicator). It appears that the steel scenario presents higher impacts than the wood scenario in almost all the impact categories considered, with the exception of the particulate matter. The impacts are significantly lower, around half of the ones in the steel scenario, in the case of human toxicity (both the cancer and non-cancer one). The other indicators present around 70-90% of the impacts than in the base case, while in a few cases the impacts are not significantly reduced: the impacts on terrestrial eutrophication are only 95% of the ones in the steel scenario, while 92% in the cases of marine eutrophication and water use. Finally, an increase of particulate matter release can be observed, up to 129%. This is due to the use of the wood; in fact, the glued laminated timber dataset includes wood processing with significant impacts on this indicator.
On the other hand, if the wood parts need to be replaced after 15 years the results significantly change: in 10 of the 15 indicators the impacts are higher than in the steel scenario. The most noticeable indicator is the particulate matter one, where the impacts more than double, while for eutrophication (terrestrial and marine) the increase is around 30%. A decrease in the impacts can still be observed for the human toxicity indicators (54-57% of the initial impacts) and for climate change (slightly, around 97%), eutrophication – freshwater (89%), and resource use, minerals and metals, where the impacts drop to 71% of the steel scenario ones. In the other scenario analysed for wood, namely the case where wood components are re-painted with a protective coating every 7-8 years and thus are not replaced, the impacts are only slightly higher than in the base case analysed for wood. The impacts in this case are similar to the ones obtained for the steel scenario for the water use, eutrophication (terrestrial and marine) and acidification scenarios.
To conclude, it is interesting to assess can be observed that the impacts of the steel scenario are significantly lower if we consider that the steel components are re used for further applications after the end of the system lifecycle, without re-processing, and so if we allocate their impacts to both systems, namely the steel scenario with 60-years components. In this case, the impacts are reduced in all the impact categories analysed, with reductions to 51-73% if compared to the steel scenario.

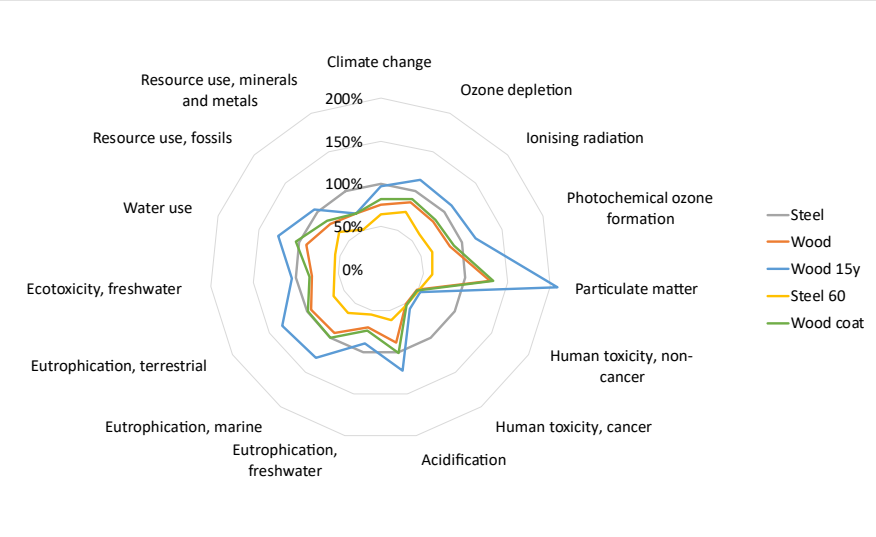
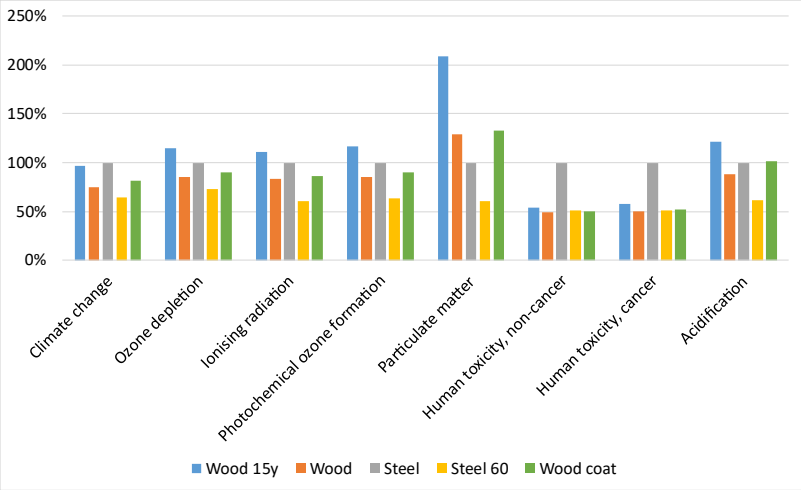


Figure 1.7. Relative results of the 5 scenarios, compared to the steel scenario, radar chart



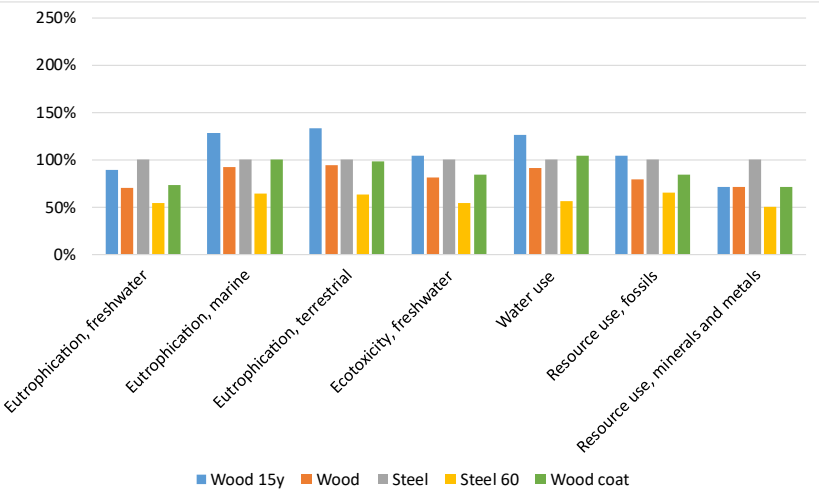


Figure 1.8. Relative results of the 5 scenarios, compared to the steel scenario, bar chart

On the other hand, the land Use indicator behaves differently. The impact of using wood instead of steel in this case is higher, and even more if the wood components are expected to be replaced during the system lifetime. The values related to this indicator are depicted in Figure 1.9. Another consideration to be made is related to the wood availability. In fact, the request of wood for this type of application can be significant considering that many sub-components are expected to be replaced (the foundations and the beams that hold the PV panels). Therefore, the application of this solution on a large scale would require an important amount of wood.

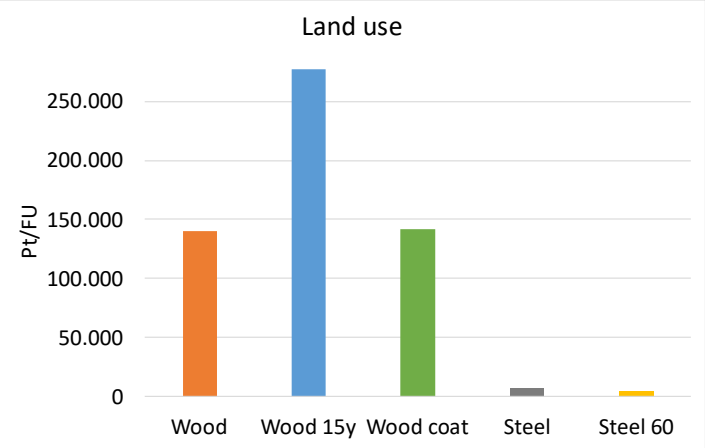


Figure 1.9. Land use indicator results

In the next sections, the details of each scenario's results are reported.

1.5.3 STEEL STRUCTURE SCENARIO

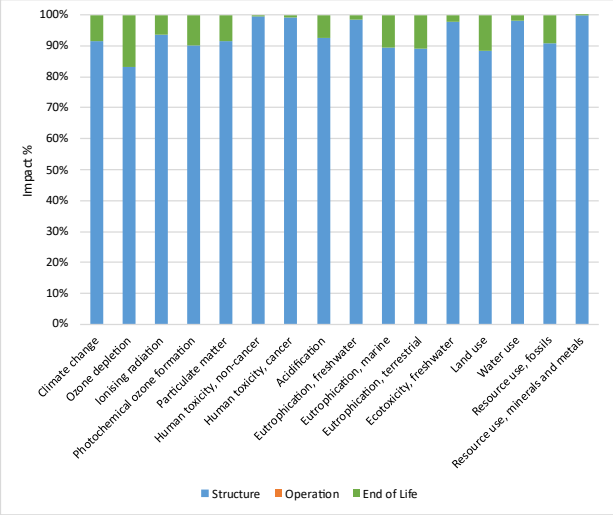


Figure 1.10. *% weight of each stage on the total impacts, steel scenario*

Figure 1.10 reports the relative weight of each stage of the lifetime on the total impact on each impact category. It can be observed that, for all categories, the structure is responsible of the majority of impacts (from around 83% in case of ozone depletion to 99.9%, in case of resource use, mineral and metals). This lifecycle stage includes the operations from the collection and transportation of all the materials to the assembly and transportation of the components to the site. A smaller responsibility on the total impacts is due to the end of life stage, namely the dismantling, transportation of the materials to the treatment plants and the treatment of the waste itself. No impacts are associated to the operational stage, since no operations or replacements are encompassed in this case.

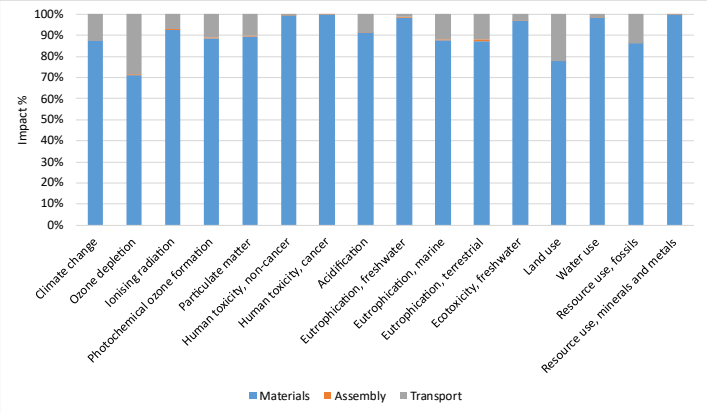


Figure 1.11. % weight of each sub-stage on the structure, steel scenario

Deepening this aspect, with a focus on the "structure" stage, it can be noticed that it is made by three main components: the actual production of the structure materials for the tracker, the assembly phase and the transport of the structure to the site.
The phase in charge of almost all the impacts is the one represented by the materials. This includes the materials extraction, the transportation to the manufacturer's sites, and the processing of these materials.

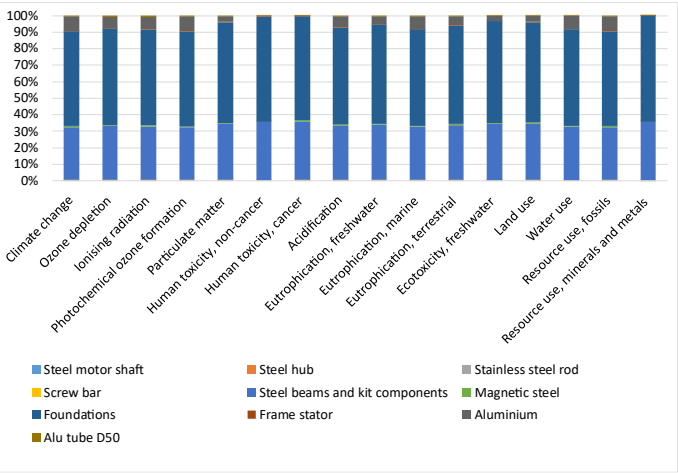


Figure 1.12. % weight of each sub-element on the tracker, steel scenario

Zooming on the materials, that showed to be the responsible of most impacts, it can be noticed that between 60% and 70% of the impact is represented by the foundations, and 30% by the steel beams and kit components. These are the elements for which the potential replacement with wood components is assessed. This is an important aspect to be taken into account when comparing the scenarios.

1.5.4 STEEL STRUCTURE SCENARIO, 60 YEARS

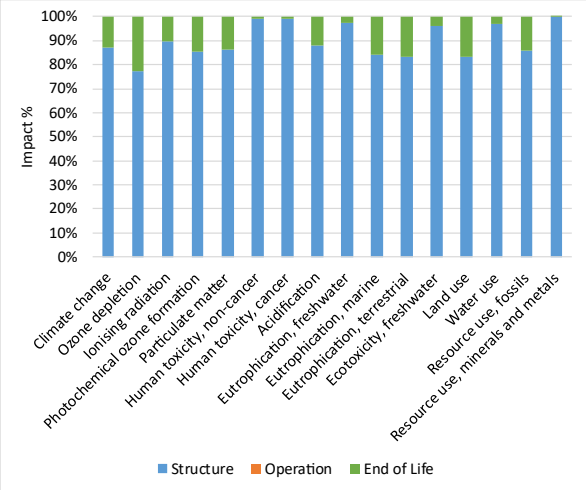


Figure 1.13. % weight of each stage on the total impacts, steel 60 years scenario

This scenario is a variation of the previous one. The difference is noticeable in terms of absolute values, as seen in the previous tables and diagrams, but not in the relative ones, as can be seen in Figure 1.13.

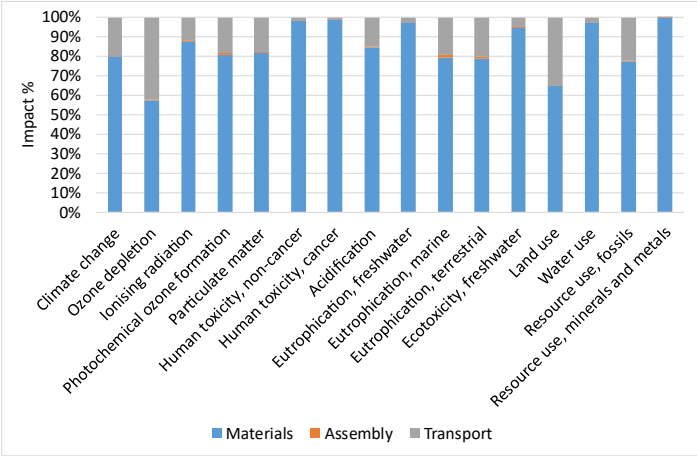


Figure 1.14. % weight of each sub-stage on the structure, steel 60 years scenario

It should be considered that the impacts of the materials used (steel structural components) is reduced by 50%, since the components are used for further applications and their impacts are allocated to the different systems; therefore, the impacts of the materials used have a lower weight than the one observed in the steel scenario on the total, while the relative impact of transport on the total is higher, since the total weight of the structure is the same. In any case, for all the indicators analysed the materials are responsible of the majority of the impacts.

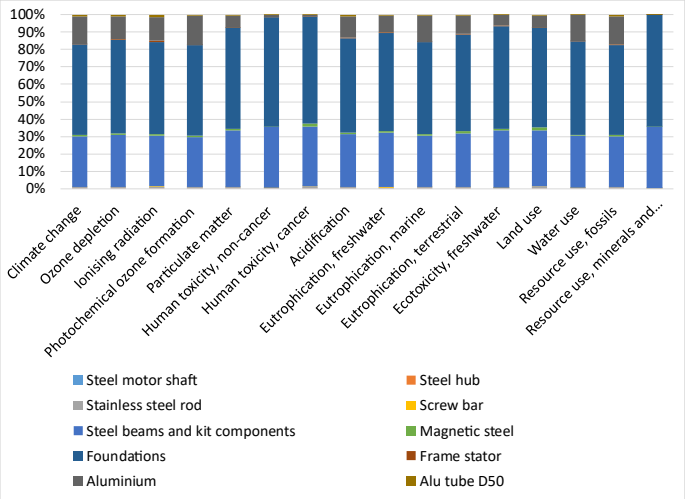


Figure 1.15. % weight of each sub-element on the tracker, steel scenario

The details of the sub-components of the structure are not significantly different than the ones observed for the steel scenario. Also in this case, between 80% and 100% of the total impacts is related to the materials that compose the steel beams and kit components, and the foundations (only this component is responsible of between 50% and 64% of the total impacts, in all the indicators assessed.

1.5.5 WOOD STRUCTURE SCENARIO

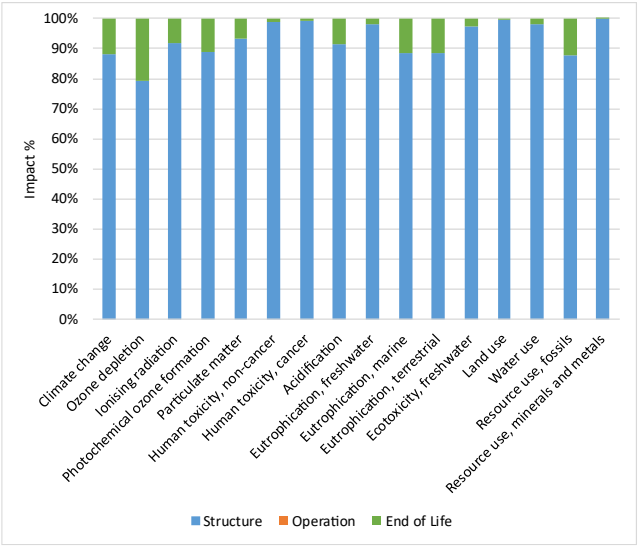


Figure 1.16. % weight of each stage on the total impacts, wood scenario

In Figure 1.15 the relative weight of each stage of the lifetime for each impact category are presented.
Also in this case, as seen for the steel scenario, the operation stage is not responsible of any impact, considering that no activities nor substitutions have to be carried out in this scenario.
The majority of impacts are associated to the structure itself, while only a small amount (maximum 20% of the total) to the end of life of the components.

Compared to the steel scenario, the weight of the structure on the total impacts in many of the indicators under assessment appears to be slightly lower. This consideration, in any case, should be made keeping in mind that these are relative values, while the absolute values, as seen in the previous diagrams and tables, are usually lower than in the steel scenario.

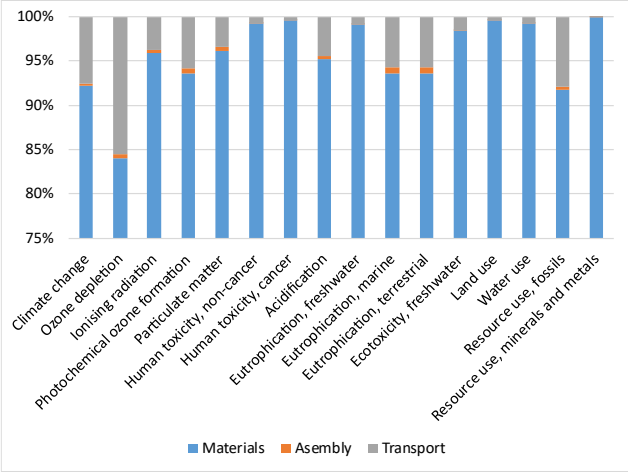


Figure 1.17. % weight of each sub-stage on the structure, wood scenario

As seen in the previous scenario, considering the structure only, three main components can be identified: the actual production of the structure materials for the tracker, the assembly phase and the transport of the structure to the site.
While the transport only counts for a very small percentage of the impact of the structure, the main contribution is given by the materials used (68% for ozone depletion, and above 95% in several other cases).

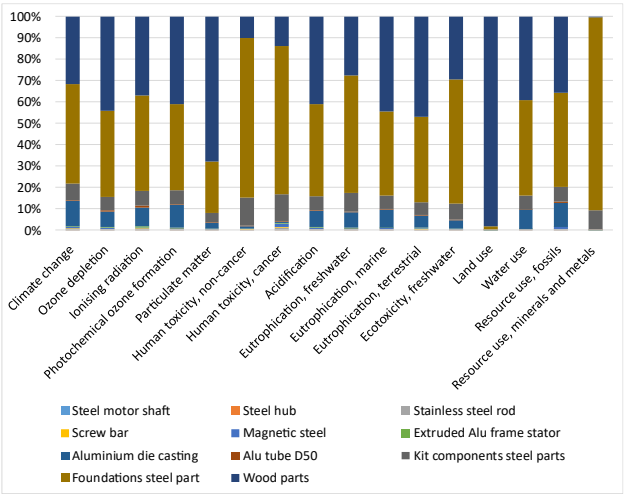


Figure 1.18. % weight of each sub-element on the tracker, wood scenario

For what concerns materials, it can be observed that the wood elements are the ones responsible of an important percentage of the impacts. They represent almost all the impacts related to land use (98.2%), while 68% of the ones of the particulate matter indicator. For the other impact categories, the wood part count for 30%-45% of the total. The indicators for which these elements play a minor role are the human toxicity ones (10% for the non-cancer indicator, and 13.7% for the cancer one). Finally, the resource use, minerals and metals indicator does not see a crucial role of the wood elements, that only count for 0.4% of the total impacts (differently from what observed in the case of steel components).

1.5.6 WOOD STRUCTURE SCENARIO, WITH REPLACEMENT

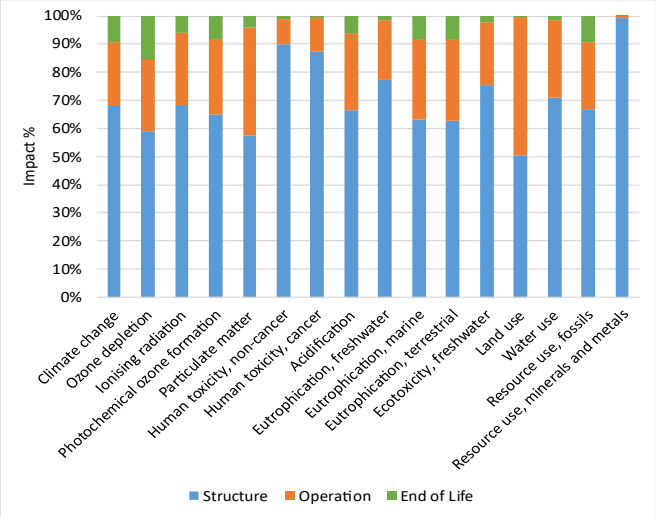


Figure 1.19. % weight of each stage on the total impacts, wood replacement scenario

This scenario, differently from the previous ones, includes the operation stage. In fact, the wood elements are supposed to be replaced after 15 years of operation, because of the strength requirements of the structure. Therefore, in the operation stage the new wood elements production, the assembly and their disposal are considered. This stage counts for around 9-38% of the total impacts, depending on the indicator analysed, with the extreme peaks of 0.4% on case of the resource use minerals and metals, and 49.3% of the land use ones. This aspect is in line with the considerations made in the initial comparison of the impacts; in fact, the land use is higher in case of elements made from wood than ones made from metals.

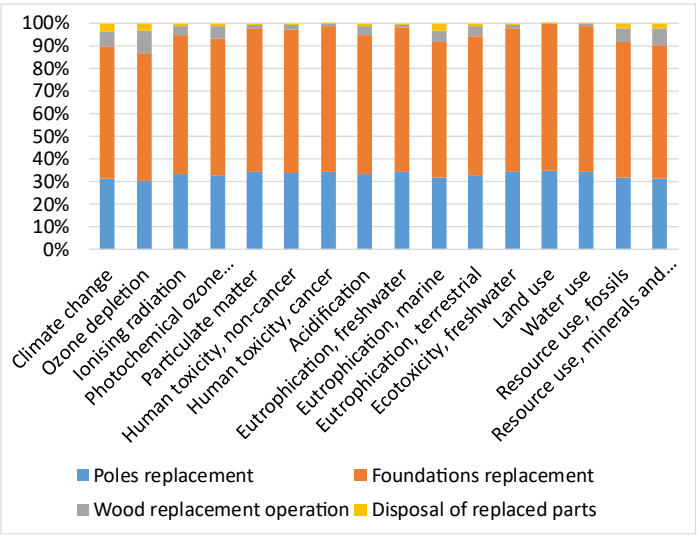


Figure 1.20. % weight of the operation stage, wood replacement scenario

The operation stage consists in the production of the wood elements needed to replace the original ones after 15 years, the dismantling of the structure to replace the specific parts, and the installation of the new components. In addition, the end of life treatment of the original wood components is considered.
In this case, it can be observed that, from the selected environmental categories perspective, most of the impact is due to the production of the new wood components (beams and foundations), up to between 87% and 99.9% of the total. A lower percentage is due to the operation processes, namely the mounting and dismounting of the structure to install the new wood elements, in form of electricity consumptions and use of machinery fuelled by diesel. These percentages are up to 9.6% of the total impacts (in the case of ozone depletion indicator), while are lower in the other ones. Finally, a small portion of the impacts is due to the disposal of the original wood parts, with a peak of 3.8% for climate change indicator, 3.4% and 3.3% for marine eutrophication and ozone depletion, and lower values for all the other ones.

1.5.7 WOOD STRUCTURE SCENARIO, WITH PROTECTIVE COATING

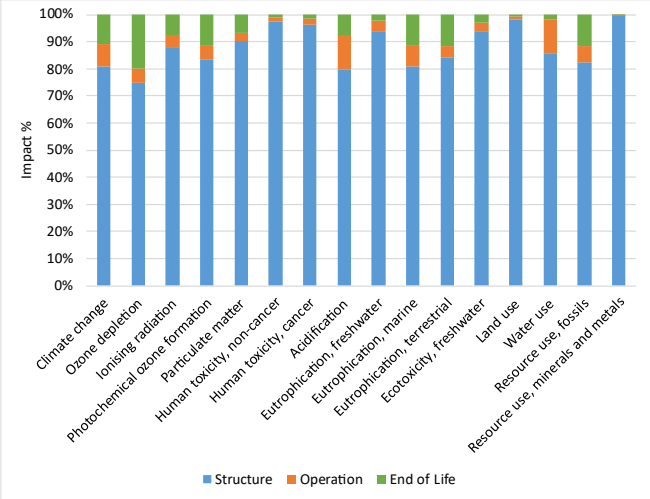


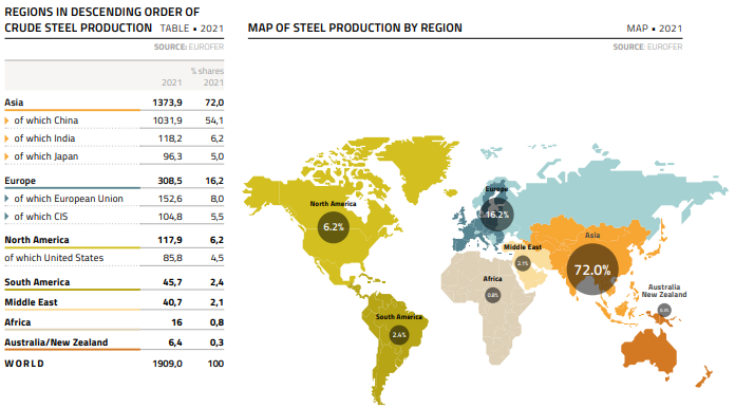
Figure 1.21. % weight of each stage on the total impacts, wood coating scenario

Also this scenario includes the operation stage. In fact, the wood elements are expected to be painted with a protective coating every 7-8 years, as suggested by the experts, and thus 4 times along the total system lifetime, modelled with an alkyd paint.
This stage represents around 8-12% of the impacts for some of the indicators analysed, such as acidification, water use, climate change and eutrophication, marine. In the case of other indicators, the weight of this stage on the total impacts is more limited.
In general, it can be said that the difference with the basic wood scenario is quite limited, with a few percentage point increase. In the case of some indicators, namely the ones mentioned beforehand (water use, climate change and eutrophication, marine), the difference is noticeable, with around 8%-14% increase in the total impacts, due to the use of the painting.

1.6 RAW MATERIAL AVAILABILITY

1.6.1 STEEL STRUCTURES

For how the SYMBIOSYST configuration is defined, it can be considered that, for 1 hectare field, around 100 trackers are needed. Each tracker requires around 795 kg of steel components, that means around 8 tons for the analysed configuration and 79.5 tons of steel for the whole configuration in 1-hectare territory. Hereafter, a discussion of how and where this material could be retrieved is presented.



REGIONS IN DESCENDING ORDER OF CRUDE STEEL PRODUCTION TABLE • 2021
SOURCE: EUROFER

	2021	% shares 2021
Asia	1373,9	72,0
of which China	1031,9	54,1
of which India	118,2	6,2
of which Japan	96,3	5,0
Europe	308,5	16,2
of which European Union	152,6	8,0
of which CIS	104,8	5,5
North America	117,9	6,2
of which United States	85,8	4,5
South America	45,7	2,4
Middle East	40,7	2,1
Africa	16	0,8
Australia/New Zealand	6,4	0,3
WORLD	1909,0	100

Figure 1.22. European steel production. Source: European-Steel-in-Figures-2022-v2.pdf

We note that 4 countries in Europe have a production that stands out from the crowd: Germany, Italy, Spain and France.

According to Eurofer and the report they published in 2021 named Eurpean Steel in Figures, we note that the European crude steel production is maintained between 150 and 160 million tons per year since 2012.

Regarding the recycled steel, EuRIC published a report named Metal Recycling Factsheet in February 2020. According to this European institution specialized in circular economy, “European steel scrap recycling collects and re-processes more than the demand for steel scrap in the EU. Hence, there is no steel scrap shortage in the EU.”
Eurofer tell us that 56% of European steel is made from scrap steel. When we have a look on the raw materials given by Valmont Industry, the steel provider of our steel structure, we see that around 50% of the steel used is from recycled steel. These values are coherent. Finally, we can note that we will need 8 tons of steel to build the whole structure.

1.6.1.1 *PROXIMITY OF THE RESOURCE*



Figure 1.23. Map of the repartition of the steel industry production sites in the EU28 published by Eurofer on the circular economy of steel.

If we have a look on the repartition of the secondary steelmaking location, we can see that there is a lot a factory all around Europe. We note that our Italian steel provider is in Bolzano. The factory we work with is not settled close to a primary steelmaking (300 km away. It means that the primary steel we will use is going to travel a lot before reaching the site in Barcelona.

Our project does not require a huge amount of steel, and we would point out that a total of 8 tonnes is used to build the structure. If we compare the value of raw materials and the way the steel industry operates today, we can see that we're right on target. The availability of steel should not be the limiting factor.

1.6.2 WOOD STRUCTURES

Similarly to what said for steel, it is crucial to understand how the wood needed for the wood elements of the structure could be retrieved. In this case, for a 1-hectare configuration, steel would still be needed, around 33 tons (3.3 tons for the SYMBIOSYST configuration). In addition, the wood requirement would be of around 520 kg for each tracker, that means, in case of 1 hectare, around 52 tons of wood (5.2 tons for the SYMBIOSYST configuration). This is an important amount of wood: in case of Pinus sylvestris, for example, it can be considered that an adult tree can achieve a weight of around 3 tons, for a height of around 35 m. This means that, to build a 1-hectare agri-PV field, in the scenario with the non-replacement of wood elements, the wood equivalent to at least 18 adult trees (with an average age of 300 years), would be needed. Since the wood is to be provided under the form of poles and beams, it is not possible to take advantage of all the tree trunk,

but only a portion of it can be used. Therefore, even more trees would be needed to cover the necessities of the plant. All these aspects should be translated into considerations on the sustainability of the solution and local availability, as will be discussed later in this section.

As already presented in the Sustainability, wood modelling section, several types of wood were taken into account for the study. In a first stage of the analysis, the focus has been on the comparison between types of wood available locally. This analysis is presented hereafter. As it will be explained, successively, it was decided to focus on the structural engineered woods, since they provide better performances in terms of resistance and durability, although their environmental impact is higher due to the more intense processing they are subject to.

First of all, it was considered that the aim of this project is not to restrict the analysis to Spain. To achieve this, it is important to study the availability of the main resource in neighbouring countries too.

Pinus Sylvestris and Pinus Pinaster were selected because of their natural capacity for resistance, durability, reliability and, above all, availability. As can be observed in the diagram, there are a total of 279 million m3 of maritime and Scots pine in France.

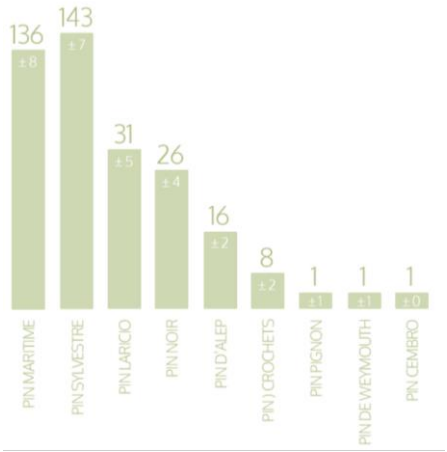


Figure 1.24. Number of pine trees in France in millions of m3.

Source: http://www.pinsdefrance.com/les-pins-de-france/chiffres/

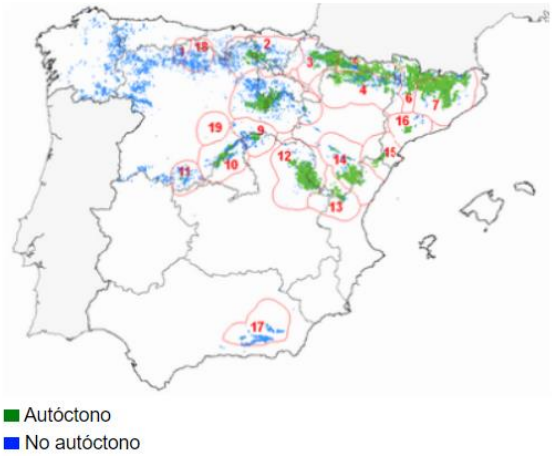


Figure 1.25. Pinus Sylvestris

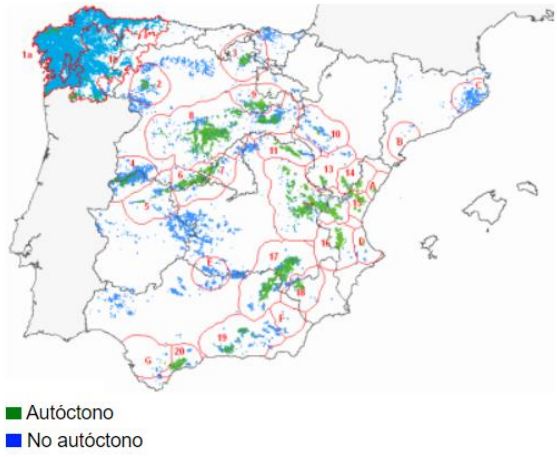


Figure 1.26. Pinus Pinaster

The focus is on the pines identified as non-native, which means that they are farmed pines. As shown in the legend, these are the blue dots found in large numbers on the Atlantic coast, in the north and north-west of Spain.

From the Almazcara forestry maps, it can be seen how the distribution of Scots pine (Pinus Sylvestris) is mainly in Eastern Europe, unlike maritime pine (Pinus Pinaster), which has a strong presence especially on the Atlantic coast.



Figure 1.27. Pinus Pinaster

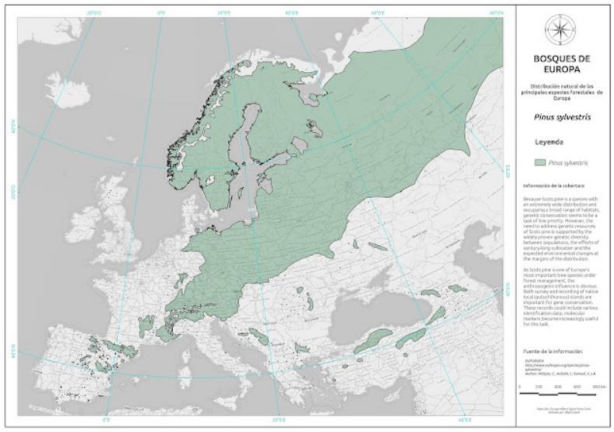


Figure 1.28. Pinus Sylvestris

Maps showing the location of the various pine trees chosen in Europe according to Almazcara forestry

On the other hand, as it was mentioned, the glulam wood is expected to be used in this project. The provision of this wood is widespread in Europe, the main producer being Germany and Austria, for which statistic data is available. In 2022, these countries produced 2.84 million m3. The distribution of the main producers in these countries are depicted in the figure below, from the Timber-online.com.

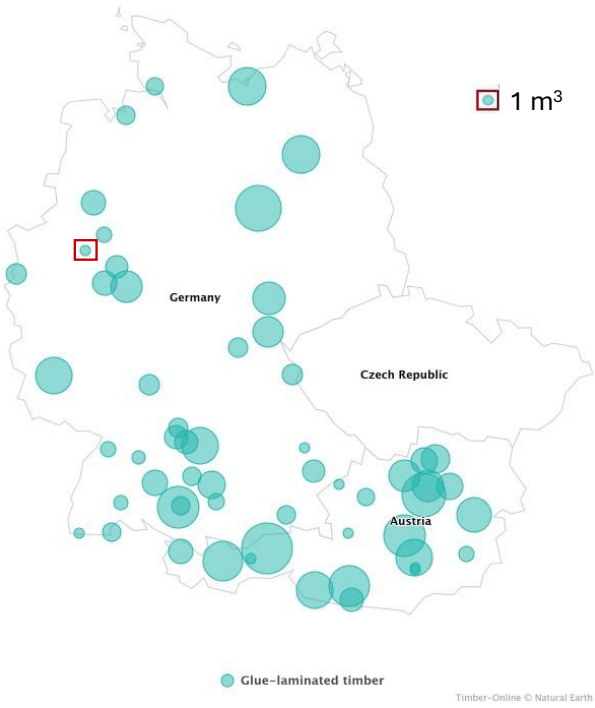


Figure 1.29. Glued-laminated timber production in Germany and Austria

In order to understand the level of maturity of the market, and the wood requirements that producing the agri-PV structures with this material would involve, an analysis has been performed taking into account the potential needs.

In 2023, based on studies performed by the JRC, the EC estimated that, if agri-PV was installed on 1% of the utilized agricultural areas of EU, it would be possible to achieve the targets set for 2030 photovoltaic electricity generation. This would correspond to a total of 944 GWp.

Considering the current glulam market, if 5% of the agri-PV capacity needed to achieve this European target was covered with wood-structured systems, almost 50% of the current Germany and Austria's glulam generation would be needed. If 20% of the demand were covered by glulam structures, over 190% of the current generation would be needed.

Two additional scenarios have been evaluated, considering a potential expansion of glulam market in the following years. According to the Glulam Market Outlook developed by EMR Claight2, the market is projected to grow at an annual rate of 5.2%. To evaluate this potential market expansion, two scenarios were evaluated, in which the market capacity grows by 4% (scenario 1) and by 6% (scenario 2) each year, to evaluate how this could affect the supply needs.

[2] Available at: https://www.expertmarketresearch.com/reports/glue-laminated-timber-glulam-market

These figures, depicted in Figure 1.30, show how critical the glulam supply can be if large scale plants are considered. In fact, the whole current glulam market would only be enough to cover around 10% of the current demand (achieving around 13% in case of market expansion of 6% yearly). Nevertheless, the current glulam applications would still need to be covered, and a massive market growth, that is currently not expected, would thus be needed to cover all the demand.

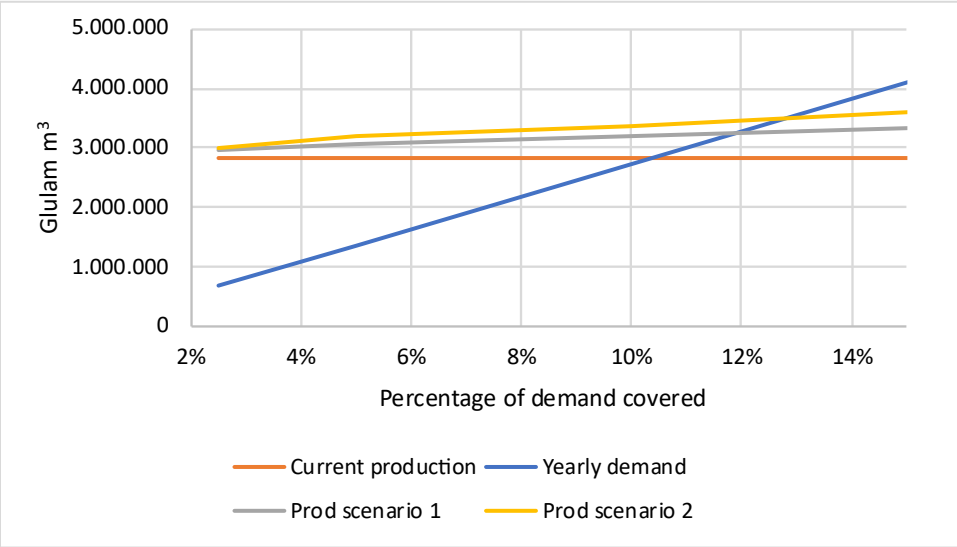


Figure 1.30. Glulam generation and demand scenarios

Said that, it could be concluded that the availability of the wood is currently a limiting factor if large scale plants are to be installed. In fact, not only the resource is limited, but so is the market maturity of glulam, that would not be able to cover, in the next few years, an important increase in the volume of wood requested to build agri-PV plants. On the other hand, if the application is a small-scale plant, the glulam supply would not be an issue.

1.6.2.1 *PROXIMITY OF THE RESOURCE*

Firstly, it should be noted that the wood used must comply with PEFC (Plan European Forest Certification) certification, a guarantee of control over wood resources in the future. In this section, the local supply of resources is assessed. Knowing that the present project will be developed in Spain, it is respectable to consider wood resources coming from French, Portuguese as well as Spanish forests. With this in mind, a number of French and Spanish companies that meet the desired criteria were identified.

Table 1.6. French and Spanish operators who use autoclave treatment and have PEFC certification.

Provider	Web	Headquarters	Factory	Origin of the raw material
Eiforsa	https://eiforsa.es/		Huesca, Zaragoza (Spain)	
Fitoforestal	https://www.fitorforestal.com/	Palafrugell, Girona (Spain)	Oliveira de Frades (Portugal) Pegões (Portugal)	

Provider	Web	Headquarters	Factory	Origin of the raw material
SEF	www.sef-scierie.fr	45530 VITRY-AUX-LOGES	45530 VITRY-AUX-LOGES	
France Wood Imprégnés	www.francewoodimpregnes.fr	Le Cerizet 42210 Woodset-Les-Montrond France	Woodset-les-Montrond (42),Meymac (19),Arc-les-Gray (70)	
Moulin Scierie	www.moulin-sa.com	DUNIERES (43)	DUNIERES (43)	Massifs forestiers d'Auvergne et de Rhône-Alpes
Groupe Barillet	www.groupe-barillet.fr	45110 Châteauneuf sur loire	A bit everywhere in France: South → Pau (64)	France
Bedora Wood	www.bedora-wood.com	Pomarez (40)	Pomarez (40)	Forêt de Landes
SIRA	https://www.sira-bois-autoclave.fr/produits/piquets-pour-l-agriculture			

From the analysis, it appears that getting local Spanish, French or Portuguese wood that respects European environmental commitments is quite easy.

1.7 COST

1.7.1 STEEL STRUCTURES

In this section, an evaluation is performed in order to compare the cost of the elements that can be either in wood or steel. Three types of components are considered: the poles (foundations), the beams and the tubes. For pole, for a total the steel structure, for each tracker, the foundations are 4 poles; the replaceable part is around half of the whole weight of 59 kg each. 18 beams are used to hold the PV panels: in this case, each beam has a weight of 4.4 kg. Moreover, 3 longer tubes are used transversally to the beams, each of them weighting 66.9 kg. The cost per kg of each of these elements is indicated in the following table, together with the total weight needed per tracker and the final cost for each of them.

Table 1.7. Steel weight and cost estimation for 1 tracker

Element	Total weight (kg)	Unit cost (€/kg)	Total cost (€)
Poles	236	1.8	424.5
Beams	79.2	1.35	106.9
Tubes	200.76	1.75	351.3

The total cost per tracker of these elements would thus be 883 €, that means, 8'830 € for the whole SYMBIOSYST configuration of 10 trackers.

1.7.2 WOOD STRUCTURES

The cost of the wood elements strictly depends on the specific type of wood used, on the location where it is produced and purchased, and on the suppliers selected. In any case, it was possible to estimate an average price for the wood elements of the structure, according to the market prices.
The price of different types of wood has been estimated, in order to provide a reliable range of prices.

The estimations for the were performed by using the ITeC software in case of pinus elements, while with the price calculator for Spain market developed by CYPE Ingenieros, S.A.

Table 1.8. Wood costs estimations

Type	Price	Unit	Source
Pinus pole, polished	788,12	€/m3	ITeC
Pinus pole, rough	718,72	€/m3	
Pinus beam, polished	755	€/m3	
Pinus beam, rough	766	€/m3	
Glulam	1097,75	€/m3	CYPE Ingenieros, S.A.

In 1 tracker as foreseen for this configuration, as defined within the project, the elements considered are:

- 4 poles sized: 14 cm x 24 cm, 2.45 m length.
- 3 tubes sized: 10 cm x 28 cm, 17 m length (in total).
- 18 smaller beams sized: 8 cm x 12 cm, 0.8 m length.

In terms of total material used, this corresponds to the amounts reported in the following table.
The calculation of the total cost of the wood elements is thus evaluated considering the average cost per m3 of glulam, and the cost of poles and beams in the case of pine wood, for which the polished type has been preferred. The total costs obtained are reported hereafter.

Table 1.9. Amount of wood needed and final total cost estimation for 1 tracker

Wood type	Element	Amount (m3)	Cost (€/m3)	Cost (€)	Total Cost (€)
Pine	Poles	0.33	788.12	2'60.05	724.2
Pine	Beams and tube	0.615	755	4'64.18	
Glulam	Tot	0.945	1097.75	10'37.11	1'037.1

The total cost of the wood elements for 1 tracker thus ranges between 724.2 €, in case the pine wood is used, and 1'037.1 € when glulam, structural wood is selected. This means a range between 7'242 € and 10'371 € for the 10 trackers, namely the SYMBIOSYST configuration.

In the scenario where the wood elements need to be replaced before the end of the structure lifetime, the total cost for these components is double.

1.8 HOLISTIC ANALYSIS

The analysis performed was aimed at comparing the option of using steel or wood for some of the components of the agri-PV structure. To do this, a holistic approach was adopted, in order to evaluate the behaviour of the two options from several points of views and considering potential risks and barriers that this choice could involve.

First of all, both materials have to ensure that the structural loads of the whole structure and PV plant are guaranteed. This means that all the components have to be strong enough to hold the system. In both cases, namely the structure with the steel or wood components, this requirement is fulfilled. It should be noted that the wood taken into account for this application is not simple beam wood, but engineered structural wood specifically made for outdoor and architectural applications, since they are resistant and long-term. Further research, based on wood experts' studies and tests, are still necessary to assess the details of the metal joints that connect the wood elements with the remaining steel components of the structure.

In addition to this, it is crucial that the elements can last and maintain their characteristics throughout all the plant lifespan (30 years). In this case, some risks have been identified because of the high humidity conditions in which the structure operates and to the potential biological attacks received because of the agriculture fields where it is placed. This risk looks to be especially present for the wood components; although an autoclave treatment is expected to be made, the producers only guarantee their products for around 15 years. This means that there is a risk of not fulfilling the requirements after this period. As emerged in the analysis, this could imply serious problems since the replacement of the wood components after half of the system lifetime means that massive works have to be done to the plant. As a consequence, the operation of the plant should be interrupted for a period, with a consequent loss of electricity generation, and intrusive operations should be made to remove the old components and install the new ones. This can also be translated in a stability risk, namely the fact that the structure does not operate optimally after the re-mounting because of not perfect contact between the electrical components. In conclusion, the replacement of some components would not be a simple operation.

With regard to sustainability, an LCA of the two types of structure has been performed to compare the option with wood and steel. In general, the structure with the wood elements performed better than the steel ones in almost all (14 out of 16) of the indicators considered, with the exception of land use and particulate matter generation. This can thus mean that, from a general perspective, the use of wood elements improves the environmental performances of the structure. It should be noted that this has been evaluated considering glulam wood (structural resistant wood). Anyway, the selection of the wood type can highly affect the results: in fact, the use of simple non-treated beams instead of the glulam means a lower environmental impact, up to around only 11% of the impacts on glulam on average; this would involve even higher advantages in terms of environmental performances of the wood structure. Nevertheless, in this case the elements would not be resistant, they would have a reduced durability and the beams would have a limited length. Therefore, this option, even if ensuring lower impacts, has been discarded because it is not realistic.
Moreover, some scenarios were created to evaluate the sensitivity of results to some important factors. In fact, if the wood components are not able to operate along the 30 years of lifetime, and thus need to be replaced at a mid-point, the results of the LCA significantly change; in this case, the results are not as clear as they are in the base case. In fact, in this case the wood structure performs better than the steel one in only 5

out of the 16 environmental indicators assessed. This means that, if the elements have to be replaced, it is not convenient to use wood. Alternatively, the option of covering the wood elements with a protective paint has been assessed, considering that this activity should be repeated every 7 years. In this case, the total impacts are slightly higher than in the case of simple wood (between 0% and 14% higher). Using wood with coating would be advantageous in 10 of 16 indicators assessed, but with less important differences in these indicators than in the case of non painted wood.

Similarly, it should consider that the steel components could be used for a longer period of time than the planned 30 years. In case they are used for a second similar application, for example if after the 30 years another agri-PV plant is placed in the same field and the structure is not replaced, the impacts of these components would be allocated to both applications and, thus, the impacts per functional unit would be significantly reduced; in this case, the use of steel would be more advantageous than the use of wood (without replacement) in almost all the indicators analysed (14 out of 16). Therefore, it should be concluded that the sustainability of the solution strictly depends on the application, and especially on the lifetime of the components.

Another important aspect to assess is the availability of resources. The proposed structure would require, in the first case, about 8 tons of steel, and in the second one 3.3 tons of steel and 5.2 tons of wood. An assessment of the resource availability in Spain and close-by countries shows that this would not be a limiting factor for the feasibility of the project in both cases. In any case, if a massive amount of large-scale projects are expected to be implemented all over Europe, the availability of resources should be taken into account. In fact, it is both an issue of amount of material available and of maturity of the market. Currently, the glulam market is not mature enough to expand in the short-term and to provide materials for massive large-scale applications.

The last aspect to be mentioned is the economic cost. The comparison of costs is based on the components of the structure that can be made either of wood or of steel. For what concerns steel, the provision of the poles and beams can cost around 883 € per tracker. On the other side, the wood components can cost between 720 € and 1’040 € per each tracker, depending on the wood type. The lower range is characterized by Pinus beams and poles, while the highest cost is referred to the construction wood; this is the one that is actually suggested for the application, because of its characteristics, resistance and strength. Therefore, from an economic point of view, it can be said that if glulam is selected the cheapest option is steel, while for other types of wood, not structural and thus simplest, wood can be cheaper than steel.

ANNEX 3: LCA OF ROBOT

The Life Cycle Assessment, or LCA, is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

The process of performing an LCA analysis is standardized in two main ISO standards, recognized at the international level as the reference documents for this type of assessment: the ISO standard 14040:2006/2020 (Environmental management, Life cycle assessment, Principles and framework), that frames a common methodology to be followed when performing an LCA analysis, and the ISO standard 14044:2006/2020 (Environmental management - Life cycle assessment - Requirements and guidelines), that complements it by describing in more detail such approach, also defining specific requirements.

The standards identify 4 main phases that compose the LCA approach:

- **Goal and scope definition:** this preliminary phase is crucial to define the goal of the study performed, and to clarify the boundaries, requirements and assumptions introduced to achieve such goals.

- **Inventory analysis:** this phase encompasses the quantification of all the input and output fluxes that compose the system under assessment, throughout all its lifecycle, as well as their modelling.

- **Impact assessment:** in this phase, the quantification of the impacts of the system under consideration on different environmental indicators is performed.

- **Interpretation of the results:** this phase combines the previous ones, in order to analyze the results coherently with the methodological choices made. This is an iterative process allowing to identify potential aspects to be improved in the model, and to develop interpretations, conclusions and recommendations.

The present study is performed in accordance with the guidelines indicated in the mentioned ISO standards, and the present report is structured accordingly.

1.1 GOAL AND SCOPE

1.1.1 GOAL

The goal of the present study is to perform an LCA study to assess the environmental performance of the inspection and monitoring systems for SYMBIOSYST.

More precisely, SYMBIOSYST uses an autonomous robotic platform tooled with sensors to acquire data to evaluate several environmental and plant health and growth parameters. The robot moves along the plant lines and reads on a plant-by-plant basis, with close-up readings, which gives very fine granularity.

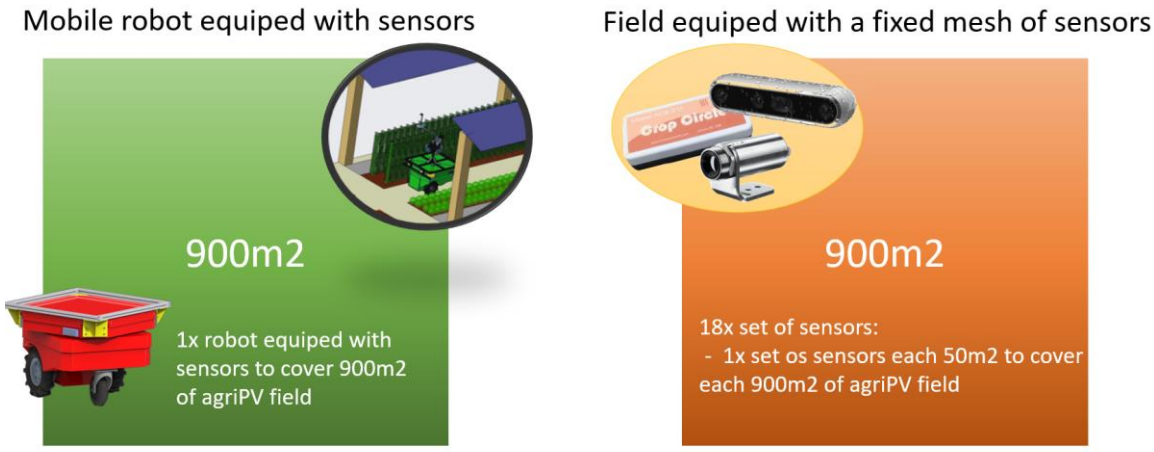


Figure 1.1. Visual comparison of the two monitoring strategies for agriPV fields: mobile robot with sensors vs. fixed sensor mesh (reference area: 900 m²)

In parallel, an alternative scenario is considered based on a hypothetical mesh of fixed sensors, which would need to be installed across the field in order to collect data equivalent to that gathered by the robot. While the autonomous mobile robot is already built and soon installed at the demonstration site in Barcelona (Agropolis) as part of the real implementation of the project, the sensor mesh is a conceptual setup consisting of RGB cameras, thermal cameras, and spectral sensors distributed over the land. The comparative assessment therefore does not evaluate two systems already in use, but rather compares the environmental impact of two potential strategies for data acquisition: deploying a single mobile robot equipped with sensors, or installing multiple fixed sensors to cover the same area and collect the same type of information. This comparison aims to determine which approach results in lower environmental impact within the context of agricultural monitoring under agrivoltaic installations. The aim is to evaluate the impact of the elements composing the system on the different impact categories selected, and their combination in the different configurations.

The analysis will be performed using the software SimaPro, that allows to model the system analyzed and to evaluate the corresponding impacts on the categories selected.

1.1.2 SCOPE

1.1.2.1 *SYSTEM ELEMENTS*

The present study includes two elements of the agrivoltaics data acquisition system: the autonomous robotic platform, which will be soon installed and operating at the demonstration site in Barcelona (Agropolis), and a hypothetical mesh of fixed sensors that would be required to collect equivalent data over the same monitored area. The details of their composition and the modelling of their life cycles are presented in Section 3.
Regarding the steel and other metallic components of the robot, the analysis assumes these elements are specifically dedicated to this application and will be sent for recycling at the end of their useful life (estimated at 10 years).

As the agrivoltaic plant is not yet fully operational, the analysis is conducted ex-ante and is not based on real operational data. The inventory for the robot is built from actual design and construction data, while its use phase is modelled based on projected operating conditions and validation in relevant scenarios.

Functional unit

The functional unit is the reference unit for which the results of the analysis are presented. It should be as simple as possible, while accurately reflecting the goal and scope of the system and enabling consistent comparisons. Typically, the unit is defined according to the characteristics of the system under evaluation. For this reason, each system element is initially analysed using its own defined unit. These are then converted to a common functional unit to allow for integrated, system-level assessment.

For the autonomous robotic platform, the defined unit (DU1) is one robot, including all mounted sensors. It is assumed that a single robot is sufficient to monitor the entire agrivoltaic field area defined in the study (i.e. 900 m^2), providing plant-level data with a frequency of one data point per hour.

For the fixed-sensor mesh, the defined unit (DU2) corresponds to one set of sensors per 50 m^2 of monitored surface, resulting in 18 sensor sets to cover the 900 m^2 reference area.

For the use phase and the global comparison, the functional unit (FU1) is defined as the monitoring of 900 m^2 over a 10-year period, which corresponds to the expected amortization period of the systems.

System boundaries

The definition of the system boundaries is crucial to determine the processes, materials and energy fluxes to be included in the analysis.

The final study system boundary is cradle-to grave. This means that the assessment encompasses all stages from the extraction of the materials used (cradle) to the treatment of the waste generated at the end of the lifecycle (grave).

The technology system lifecycle is thus evaluated along the main three processes: Upstream (everything related with the processes that occur before the technology is installed), Core (all the aspects directly related with the operation of the system) and Downstream (all the processes that occur after the lifecycle ends).

In general, the lifecycle stages and the main sub-stages that will impact the results are the following:

UPSTREAM

- Extraction,
- Transportation,
- Processing of raw materials.

CORE

- Energy consumptions during operation,

DOWNSTREAM

- Waste transportation,
- Waste treatment.

Some additional stages have been excluded from the scope of the study. For example, the auxiliary materials used during the production processes, or the water consumptions, waste generation during the production processes etc. These stages are not included since they are considered to be negligible if compared to the other stages.

1.1.2.2 *TIME AND GEOGRAPHICAL DATA REFERENCE*

The datasets used in the modelling are selected to be as representative as possible of reality. The geographic coverage of data is as follows:

- Spanish data for electricity. This refers to all the cases in which the consumption is directly from the grid, for example during the assembly/disassembly phases, since the installation is expected to be located in Baix Llobregat, in the Barcelona province.

- European data for materials processing and manufacturing processes (for example the production of metal components or the transportation means).

- European or global data for raw materials usage.

These choices depend on the availability of specific datasets. In terms of timeframe, the data used are estimations and data collected in late 2023/2024.

1.1.2.3 *DATA QUALITY*

The specific data used for the modelling of each component and the corresponding explanations are detailed in section 3 (inventory analysis).

As a general overview, data comes from detail design plans for the structure and main motor parts of the robot, or from manufacturer datasheets in the case of commercial components such as the battery, sensors and electronics. In the cases these data could not be obtained, it has been estimated according to literature.

In all cases, the data used can be categorized as “selected secondary data”, meaning they are modelled through internationally recognized datasets with confirmed direct correlation between the dataset and the actual flux. These datasets preserve the correlation between the model and the actual processes, accurately representing them in terms of geography and time period.

In this study, all the selected datasets are from the Ecoinvent 3.6 database.

1.1.2.4 *USE STAGE ASSUMPTIONS*

The use phase is included in the model. In the case of the autonomous robot, its operation involves regular movement across the monitored area, powered by an electric motor, and therefore includes a certain level of energy consumption. The considered usage scenario is assuming intensive daily monitoring. Energy consumption is modelled based on estimated operating time, average distance covered, and battery specifications. Minor maintenance operations are expected but are considered negligible in terms of material or energy use.

For the fixed sensor mesh, it is assumed to remain continuously active throughout the monitoring period. The energy consumption of the sensors (RGB camera, thermal camera, NDVI sensor) is estimated based on manufacturer specifications and scaled to match the number of sets required to cover the entire area. No mechanical components are involved, so no moving parts require maintenance. However, for simplification purposes, no replacement of sensors is considered over the system’s lifetime, assuming a sufficiently long operational durability.

1.1.2.5 *WASTE TREATMENT APPROACH*

In order to evaluate the impact of the End-of-Life stage for the robotic platform, a disposal scenario has been defined in the model. It assumes that 98% of the steel structure is correctly disassembled, while the remaining 2% is sent to landfill. No reuse is considered. The recycling process itself is not included in the system boundaries, following the Polluter-Pays Principle (PPP), and only the transport to the treatment facility is accounted for.

Regarding the sensor set, a simplified "dummy" component has been introduced to represent its end-of-life treatment. It assumes the same logic: 98% disassembly and 2% landfill, without modelling specific recycling processes. This placeholder will be refined once more detailed data on the components and materials of the sensors become available.

1.2 INVENTORY ANALYSIS

To simulate the described scenarios, each component of the robotic platform and mesh of sensors was modelled. This section presents the modelling assumptions applied in SimaPro and lists the datasets used to represent the materials, components and processes involved. In some cases, technical details are provided — such as the full names of the datasets used or the structure of the model — to ensure traceability and allow deeper understanding if needed. However, this level of detail is not essential for the general interpretation of the analysis.

1.2.1 COMPOSITION AND INVENTORY OF THE ROBOTIC PLATFORM

The robot's physical structure is modelled based on the actual design developed by the research team for the SYMBIOSYST project. It consists of a steel chassis, motor system, wheels, and mounting components for the onboard sensors and electronics. Figure 1.2 shows the robotic platform for better understanding.



Figure 1.2. Photo of the mounted robot.

All materials and manufacturing processes were selected from the Ecoinvent 3.6 database using "Cut-off, System" methodology.

Table 1.1. List of simple datasets used in the model

Dataset in SimaPro	Material/process in Ecoinvent 3
Aluminium ingot	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | Cut-off, S
Aluminium recycled	Aluminium, cast alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner | Cut-off, S
Aluminium cast process	Casting, aluminium, lost-wax {RoW}| casting, aluminium, lost-wax | Cut-off, S
Extrusion Aluminium Process	Section bar extrusion, aluminium {RER}| processing | Cut-off, S
Extrusion steel process	Impact extrusion of steel, hot, 3 strokes {RER}| processing | Cut-off, S --> the 3 strokes one is selected, since it is the average, and the info is not available
Stainless steel manufacturing Process	Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S
Steel average manufacturing Process	Metal working, average for steel product manufacturing {RER}| processing | Cut-off, S
Zinc coat process	Zinc coat, pieces {RER}| zinc coating, pieces | Cut-off, S
Medium car diesel	Transport, passenger car, medium size, diesel, EURO 5 {RER}| transport, passenger car, medium size, diesel, EURO 5 | Cut-off, S

Steel components

The steel parts of the robot were modelled in two separate processes: _Steel_Parts and _Steel_Parts (60%). These two datasets together account for the entire steel content of the robotic platform, excluding the steel contained within the battery and the slip ring, which are modelled separately. A total of 285 kg of steel is considered, including losses due to transformation processes such as cutting, bending, and welding, which are estimated at 10%. The welding process itself is included as a separate entry. In the variant _Steel_Parts (60%), it is assumed that 60% of the steel comes from recycled scrap, reducing the environmental burden associated with primary steel production. The mass of recycled content is estimated as 285 × 0.6 = 717 kg. All materials and processes are sourced from the Ecoinvent 3.6 database under the “Cut-off, System” methodology. Table 2 below summarizes the key datasets used.

Table 1.2. Key steel components of the robot model.

Dataset (SimaPro)	**Amount**	**Unit**	**Comment**
Steel 2nd	171	kg	60% recycled steel content
Steel average manufacturing	114	kg	Includes 10% loss from cutting, bending, welding

Dataset (SimaPro)	Amount	Unit	Comment
Welding, arc, steel (GLO)	5	m	Steel welding for frame assembly

Aluminum parts

The aluminum components of the robot are modelled through the processes _Aluminum_Parts and _Aluminum_Parts (60%). These represent all aluminum elements included in the robotic platform, primarily structural or protective components. In both processes, aluminum extrusion is considered as the main transformation method.

In the base scenario, 29 kg of aluminum ingots are included, along with an extrusion process. Transformation losses (cutting, forming, etc.) are assumed to be 10%, in line with standard fabrication processes.

In the variant _Aluminium_Parts (60%), the aluminium inventory is split into:

- 12 kg of primary aluminium (Alu ingot 1st)
- 17 kg of recycled aluminium (Alu recycled)

This represents a 60% share of recycled content, which significantly reduces the environmental impacts associated with aluminum production. All data are sourced from Ecoinvent 3.6, using the "Cut-off, System" approach.

Table 1.3. Aluminium inventory in the robot model.

Dataset (SimaPro)	Amount	Unit	Comment
Alu ingot 1st	12	kg	Primary aluminium
Alu recycled	17	kg	Recycled aluminium (≈60% of total mass)
Extruded aluminium in section bar (construction)	4	kg	Final transformation process

1.2.1.1 *SLIP RING*

The slip ring of the robot is modelled separately to reflect its distinct material composition and functional role. It is a small but essential electromechanical component used to transfer electrical signals or power between stationary and rotating parts of the system.

The total mass of the component is 3 kg of steel and 0.33 kg of graphite, according to the inventory defined in SimaPro. The steel portion undergoes standard transformation processes represented by the Steel average manufacturing process. No specific recycling or reuse behaviour is considered for this component at end-of-life. All datasets are sourced from the Ecoinvent 3.6 database using the Cut-off, System methodology.

Table 1.4. Slipring material composition.

Material / Process	**Amount**	**Unit**	**Comment**
Steel 2nd	3	kg	Secondary steel used entirely
Graphite {GLO} market for	Cut-off, S	0.33	kg
Steel average manufacturing process	3	kg	Includes standard transformation

1.2.1.2 *SENSORS ON THE ROBOT*

The robot integrates a set of four advanced sensors designed to acquire multispectral and spatial information from the monitored crops and environment. These are modelled as individual units in SimaPro, each with its own inventory. The sensors included are:

- NDVI sensor (Crop Circle ACS-211)
- RGBD camera (intel RealSense D455)
- Thermal camera (Optris Xi 400)
- LIDAR (OS2 REV7)

Each sensor is modelled as a product unit (1 p) and includes its main structural and electronic components, such as aluminium casing, glass, and embedded electronic boards. The materials are sourced from the Ecoinvent 3.6 database using the Cut-off, System approach.

Table 1.5. Sensors of the robot materials

Sensor	**Aluminium (kg)**	**Electronics (kg)**	**Glass (kg)**	**Notes**
NDVI	0.25	0.18	–	CropCircle ACS-211 (estimated)
RGBD camera	0.3	0.05	0.05	Intel RealSense D455
Thermal camera	0.12	0.07	0.01	Coated flat glass
LiDAR	0.3	0.147	–	Aluminium body, generic LIDAR

Screws

All screws, bolts, and similar fasteners used to assemble the robot's structural and functional components are grouped under the _Screws process in the model. These elements are made entirely of galvanized steel.

A transformation loss of 10% is considered to account for machining, fitting, and adjustments during assembly. The steel is assumed to be coated using a zinc coating process, which is included in the inventory. All data are sourced from Ecoinvent 3.6 and follow the Cut-off, System methodology.

Table 1.6. Fasteners and screw materials.

Material / Process	**Amount**	**Unit**	**Comment**
Steel 2nd	3	kg	Galvanized steel, incl. losses
Steel average manufacturing process	3	kg	Post-loss fabrication
Zinc coating process	0.5	kg	Galvanization process

Rubber

The robot includes a limited quantity of rubber parts, mainly used for sealing, shock absorption, or traction elements (e.g. tires or joints). These components are modelled under the _Rubber process, which includes 1.56 kg of synthetic rubber.

No specific transformation processes are modelled beyond the material itself. The dataset is sourced from the Ecoinvent 3.6 database, applying the Cut-off, System approach.

Table 1.7. Rubber mass

Material	**Amount**	**Unit**	**Comment**
Synthetic rubber {GLO}	1.56	kg	Global average market dataset

1.2.2 GENERIC ELECTRONICS

The robot integrates various general-purpose electronic components not directly associated with the main sensing or computing functions. These include passive circuit elements, connectors, internal switches, and electrical wiring. All of them are grouped under the _Electronics (Generic) process in the model.

In total, the electronics amount to 2.28 kg of passive components, 2 kg of toggle-type switches, and 8 m of electrical cable. No additional processing is modelled beyond material supply, assuming these elements are preassembled or integrated in commercial modules.

All datasets are sourced from Ecoinvent 3.6 under the Cut-off, System methodology.

Table 1.8. Generic electronics of the modelled robot.

Component	**Amount**	**Unit**	**Comment**
Electronic component, passive, unspecified {GLO}	2.28	kg	General passive electronics

Component	Amount	Unit	Comment
Switch, toggle type {GLO}	2.00	kg	Mechanical/electrical switches
Electrical cable	8.00	m	Standard low-voltage cabling

Onboard computer

The robot is equipped with an onboard computing unit responsible for processing sensor data, managing control algorithms, and coordinating autonomous navigation. This component is modelled under the _Computer (on board) process and includes 1.74 kg of electronics for control units. The dataset used corresponds to a general-purpose embedded computing system, such as an industrial PC or edge device, and is taken from the Ecoinvent 3.6 database using the Cut-off, System methodology. No additional materials or processes are modelled beyond the electronic control unit.

Table 1.9. Onboard computer mass.

Component	Amount	Unit	Comment
Electronics, for control units {GLO}	1.74	kg	Embedded computing system

Battery

The battery is a critical component of the robotic platform, responsible for supplying electrical energy for propulsion, sensor operation, and onboard computing. The modelled battery is a lithium-ion (Li-ion) battery pack with a total mass of 25 kg, complemented structurally by 3 kg of primary steel and 3 kg of secondary steel for its casing and internal support.

The process _Battery in SimaPro includes both the electrochemical cell inventory and the mechanical structure. The Li-ion battery dataset represents a generic industrial-grade battery system, suitable for mobile robotics applications, and is sourced from Ecoinvent 3.6 under the Cut-off, System methodology.

Additionally, a steel average manufacturing process is applied to 6 kg of material, accounting for the casing's transformation processes, including forming and assembly.

Table 1.10. Battery material properties

Component / Process	Amount	Unit	Comment
Battery cell, Li-ion {GLO}	25	kg	Core battery inventory
Steel 1st	3	kg	Primary steel casing
Steel 2nd	3	kg	Recycled steel components
Steel average manufacturing process	6	kg	Casing transformation and assembly

Operation

The operation stage of the robotic platform reflects the energy required for its autonomous monitoring missions in the field. As part of the SYMBIOSYST project, the robot performs detailed data acquisition tasks, including thermal, RGBD, and spectral measurements, moving along crop lines with high spatial resolution. This section models the energy consumption during these operations, which are assumed to occur daily and continuously throughout the year.

The energy use is derived from the robot's battery capacity and its effective working time and speed in real field conditions. The energy consumption is then scaled to the functional unit defined in the study: monitoring 900 m² over 10 years. The following modelling assumptions were adopted:

Table 1.11. Operational assumptions for the robot.

Parameter	Value	Description / Justification
Battery capacity	5.04 kWh	Nominal capacity of the lithium-ion battery pack
Operating time per full charge	8 hours	Estimated runtime under continuous full-power operation
Nominal linear speed	0.4 m/s	Maximum design speed
Effective monitoring speed	0.25 m/s	Adjusted speed accounting for turns, stops, repositioning, and manoeuvres
Effective coverage width	1 meter	Monitoring width covered by the sensor suite
Monitoring area rate	0.25 m²/s	Product of effective speed and width

Step 1: Area covered per battery cycle

Given the 8-hour operational autonomy and a coverage rate of 0.25 m²/s, the robot can monitor the following area per full charge:

$$Area_{per\ battery} = 0.25\frac{m^2}{s} * 8 * 3600s = 7200m^2$$

Step 2: Energy consumption per square meter

Dividing the battery capacity by the area covered gives the energy use per square meter:

$$Energy_{per\ m^2} = \frac{5.04kWh}{7200\ m^2} = 0.0007\ kWh/m^2$$

To align with the comparative unit used for the fixed sensor mesh (900 m²), we scale this result accordingly:

$$Energy_{per\ 900\ m^2} = 900\ m^2 * 0.0007\ \frac{kWh}{m^2} = 0.63\ kWh$$

Step 3: Monitoring frequency and annual consumption

A monitoring frequency of one data point per hour is assumed for the 900 m² reference area. This leads to:

$$Readings\ per\ year = 24 * 365 = 8760\ readings/year$$

The total energy required to monitor the same 900 m² throughout 10 years is:

$$Ten\ years\ consumption_{\,900\ m^2} = 0.63\ kWh * 8760 * 10 = 55188.0\ kWh/10\ years$$

Table 1.12. Energy consumption model for robot operation (8-hour autonomy)

Metric	Value	Unit	Notes
Battery capacity	5.04	kWh	Nominal energy storage
Operational autonomy per charge	8	hours	Estimated runtime per full battery cycle
Area covered per charge	7200	m²	Based on effective linear speed and monitoring width
Energy consumption per m²	0.0007	kWh/m²	Energy intensity of coverage
Energy consumption per 900 m² per reading	0.63	kWh	Baseline unit for comparison with fixed sensors
Monitoring frequency	8760	readings/year	One reading per hour
Energy use per 900 m² and 10 years	55188.0	kWh	Core operational impact figure for LCA comparison

All energy use during operation is modelled using the dataset Electricity, low voltage {ES} | market for | Cut-off, S. This ensures consistency with the Spanish energy context of the Agropolis demonstration site.

End-of-life

The End-of-Life (EoL) stage for the robotic platform has been modelled using the disposal scenario functionality available in SimaPro, which enables a structured and transparent definition of the treatment pathway for each material stream without having to manually assign treatment datasets to each individual component. This approach ensures consistency with the general methodology adopted in the SYMBIOSYST system.

In this scenario, it is assumed that 98% of the robot's components are correctly disassembled at the end of the system's lifetime, while the remaining 2% are considered losses, either due to degradation, operational wear or handling, and are modelled as a mix of landfilled and incinerated waste. No component reuse is considered.

Once disassembled, the robot's major subsystems — including the steel chassis, battery, sensors, generic electronics and onboard computer — are transported to appropriate treatment facilities. However, the actual recycling processes are not included within the system boundaries of the current LCA, in accordance with the Polluter-Pays Principle (PPP). This modelling choice implies that the environmental impacts associated with recycling operations are allocated to the next product system where the recovered materials would be used. As a result, only the transport to the treatment facility is accounted for in the impact assessment.

1.2.3 COMPOSITION AND INVENTORY OF FIXED-SENSORS MESH

This section describes the composition and modelling assumptions for the alternative monitoring strategy based on a fixed mesh of sensors. This system, in contrast to the autonomous robot, involves distributing sensor sets at fixed intervals throughout the field. The mesh is a hypothetical configuration constructed to ensure equivalent spatial resolution to that achieved by the robot, and serves as a basis for comparative LCA analysis.

1.2.3.1 *DEFINITION OF SENSOR SET*

Each sensor set (assumed to cover 50m2) in the fixed-sensor mesh includes the following three elements, identical to those installed on the robotic platform:

- NDVI sensor
- RGBD camera (Intel RealSense D455)
- Thermal camera

The LiDAR unit used in the robotic configuration is excluded from the fixed mesh, since that such spatial data is not required in a stationary setup. The materials and manufacturing processes of each sensor are modelled identically to those described in section 3.1.4, including aluminum casings, optical elements, and embedded electronics. These inventories are not detailed again here, but a summary is provided in the table below for reference. In addition to the sensors themselves, the fixed-sensor mesh requires several auxiliary components to ensure system operation and data processing:

- A shared processing computer is considered for every four sensor sets (i.e., 0.25 units per sensor group), which handles data acquisition and preliminary algorithm execution.
- A steel support structure of approximately 1.5 kg is assumed per sensor set, accounting for mounting poles or brackets.
- Around 40 m of electrical cable are included to connect the sensors to the computer and communication switch.
- 0.7 kg of electronics are added to represent the communication switch or control unit needed for system coordination.

These additional elements are essential for the correct functioning of the mesh and are included in the inventory to reflect the full scope of components required per sensor unit.
To cover the area defined in the Functional Unit as a reference to compare the performance of a sensor fixed mesh and the mobile robot (i.e. 900 m2), a number of 18 sensor sets are needed. Thus, the modelled sensor mesh includes 18 sensor sets.

Assumptions for modelling

For every four sensor sets (i.e., every 100 m^2), a central processing computer is assumed. This component is modelled identically to the onboard computer described in section 3.1.8, with 1.74 kg of electronics for control units, based on the Ecoinvent dataset for industrial embedded systems. Maintenance activities are excluded, based on the assumption of long sensor lifetimes and negligible interventions during the use phase.

All components are modelled using data from the Ecoinvent 3.6 database, with the "Cut-off, System" approach applied consistently throughout the assessment.

Table 1.13. Summary of fixed mesh components per 50 m²

Component	Quantity per 50 m²	Notes
NDVI sensor	1	As in robot
RGBD camera	1	As in robot
Thermal camera	1	As in robot
Computer (shared)	0,25	1 computer per 200 m² (i.e., 1 per 4 sensor sets)
Mounting/fixings	1,5kg	Steel 1st for sensors installation supports
Electrical cable	40m	40m electrical cable for sensors connector to PC and switch
Electronics for control units	0,7kg	0,7 kg for control units related with communication switch

Operation

The operation stage of the fixed-sensor mesh system has been modelled based on the continuous energy consumption of the sensor units throughout the monitoring period.

Each sensor set includes some active components: an NDVI sensor, a RGBD camera, and a thermal camera, computer and switch. Based on technical specifications and typical power requirements, the total energy consumption of a single set is estimated at 40 watts (W) during continuous operation.

This setup is designed to provide equivalent spatial coverage to the robot, with each sensor set assumed to monitor 50 m² of agricultural area. This value represents a balance between resolution and redundancy, and is based on the assumption that, within such area, plant conditions can be considered relatively homogeneous.

Energy consumption calculation

The annual energy consumption per sensor set is calculated as follows:

$$Annual\ energy = 40\ W * 24\frac{h}{day} * 365\frac{days}{year} = 350.4\ kWh/year$$

This value corresponds directly to the energy required to monitor 50 m² of field area with a fixed sensor mesh. The comparison with the robotic platform is therefore made on an equivalent functional unit: monitoring 900 m² over ten years.

Table 1.14. Energy use for fixed-sensor mesh

Metric	Value	Unit	Notes
Power demand per sensor set	40	W	Combined consumption of 3 sensors
Operating time	8760	hours/year	24 hours/day × 365 days
Monitored area per sensor set	50	m²	Assumed effective spatial coverage

Metric	Value	Unit	Notes
10-years energy use per 900 m² monitored area	63072	kWh	Directly comparable with robot scenario

End-of-life

The End-of-Life (EoL) stage for the fixed-sensor mesh has been modelled in a simplified yet consistent manner, following the same methodological approach used for the robotic platform. The model assumes that 98% of the components are correctly disassembled at the end of the system's life, while the remaining 2% are considered as material losses, due to deterioration, mismanagement or field conditions, and are treated as a mix of landfilled and incinerated waste. No reuse of components is assumed.

Each set is considered to be dismantled and sent to appropriate treatment facilities, although the specific recycling processes are not included in the system boundaries, in line with the Polluter-Pays Principle (PPP). As such, the environmental benefits associated with potential material recovery are not credited in the present system, and only the transport to the waste treatment facility is accounted for. In addition, a processing computer is included in the mesh configuration for every 200 m² of monitored area, which corresponds to one unit per four sensor sets. This component is modelled identically to the onboard computer in the robotic platform and follows the same EoL assumptions.

Mounting elements, poles, fixings or connectors are not modelled in this scenario, based on the assumption that their environmental contribution is negligible compared to the sensor and computing equipment. Likewise, maintenance operations during the use phase are excluded from the system boundaries due to their expected low material and energy requirements.

This simplified end-of-life approach provides consistency with the treatment of the robotic platform and maintains comparability between both monitoring strategies under the assumptions and constraints of the current LCA framework.

1.3 IMPACT ASSESSMENT AND INTERPRETATION

In this chapter, the methods selected for the evaluation and the obtained results are presented.

1.3.1 METHODS

The software used for modelling is SimaPro, release 9.1.0.8. The selected datasets are type "Cut off, System". The Method used for the LCA assessment is the EF 3.0 Method, developed at the European level within the Environmental Footprint initiative. The 16 environmental indicators encompassed are the following:

- Climate change (kg CO2eq)
- Ozone depletion (kg CFC11 eq)
- Ionising radiation (kBq U-235 eq)
- Photochemical ozone formation (kg NMVOC eq)
- Particulate matter (disease inc.)
- Human toxicity, non-cancer (CTUh)
- Human toxicity, cancer (CTUh)
- Acidification (mol H+ eq)
- Eutrophication freshwater (kg P eq)
- Eutrophication, marine (kg N eq)

- Eutrophication, terrestrial (mol N eq)
- Ecotoxicity, freshwater (CTU eq)
- Land use (Pt)
- Water use (m3 depriv)
- Resource use, fossils (MJ)
- Resource use, minerals and metals (kg Sb eq)

1.3.2 RESULTS OF SYSTEMS LCA

1.3.2.1 GENERAL OVERVIEW OF ENVIRONMENTAL PERFORMANCE: ROBOT VS FIXED-SENSORS MESH

In order to compare the environmental impacts of the two monitoring alternatives studied, Table 15 presents the absolute results for the 16 environmental indicators selected under the EF 3.0 method. These values are expressed per functional unit (FU), which corresponds to the complete monitoring of a 900 m² crop area over 10 years.

The environmental impacts of the robotic and fixed-sensor monitoring systems present notable differences across the selected impact categories. Overall, the fixed sensor mesh exhibits higher impacts in most categories, especially in climate change, ionising radiation, freshwater ecotoxicity, and resource use (fossils). These elevated values are primarily driven by the continuous energy consumption required to power the sensor network over the entire 10-year period and by the material intensity of distributed electronics across the monitored field.

In contrast, the robotic platform shows lower impacts in most energy-related categories, as it consolidates sensing in a single mobile unit. However, it presents relatively higher values in categories related to manufacturing complexity, such as resource use (minerals and metals) and human toxicity (cancer), reflecting the intensive use of electronics and batteries in a single unit. Although the fixed sensor mesh performs better in some material-related indicators, the operational energy burden makes it more impactful in key global warming and toxicity-related metrics.

The following sections present a detailed breakdown of the impacts of the robotic platform and fixed-sensor mesh, followed by a comparative interpretation to support strategic decisions in the context of agrivoltaic monitoring.

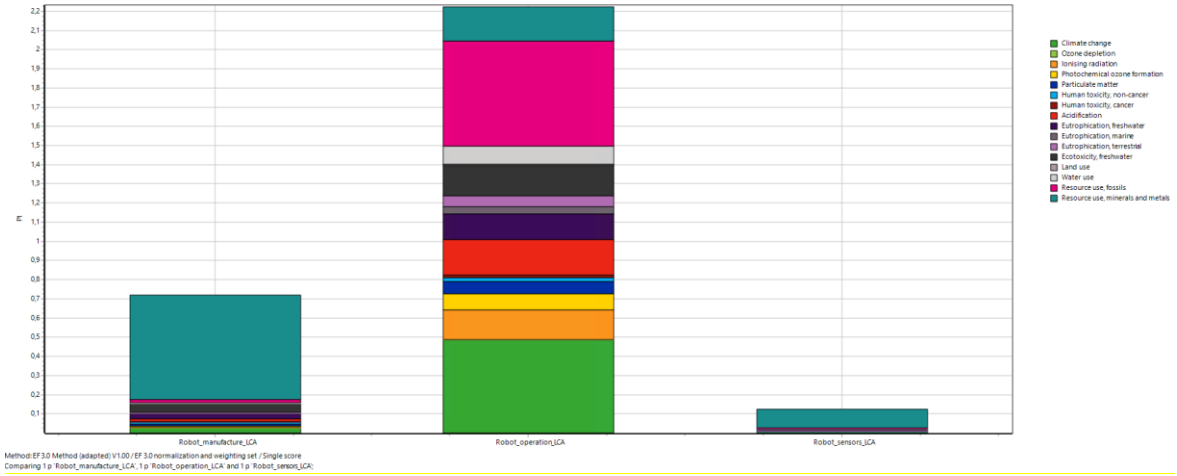
Table 1.15. Results obtained for the sensorized robot vs the fixed-sensors mesh.

Impact category	**Unit (per FU)**	**Robot**	**Sensor mesh**
Climate change	kg CO2 eq	1,98E+04	2,30E+04
Ozone depletion	kg CFC11 eq	2,12E-03	2,45E-03
Ionising radiation	kBq U-235 eq	1,32E+04	1,51E+04
Photochemical ozone formation	kg NMVOC eq	7,69E+01	8,98E+01
Particulate matter	disease inc.	6,45E-04	6,08E-04

Impact category	Unit (per FU)	Robot	Sensor mesh
Human toxicity, non-cancer	CTUh	4,21E-04	4,95E-04
Human toxicity, cancer	CTUh	1,53E-05	1,35E-05
Acidification	mol H+ eq	1,77E+02	2,11E+02
Eutrophication, freshwater	kg P eq	9,30E+00	1,16E+01
Eutrophication, marine	kg N eq	2,72E+01	3,17E+01
Eutrophication, terrestrial	mol N eq	2,85E+02	3,34E+02
Ecotoxicity, freshwater	CTUe	4,74E+05	6,01E+05
Land use	Pt	1,01E+05	1,19E+05
Water use	m3 depriv.	1,30E+04	1,49E+04
Resource use, fossils	MJ	4,43E+05	5,09E+05
Resource use, minerals and metals	kg Sb eq	6,11E-01	7,98E-01

1.3.2.2 *DETAILED IMPACT RESULTS: ROBOTIC MONITORING SYSTEM*

The environmental performance of the robotic monitoring system was assessed considering its three main life cycle stages: manufacturing, operation, and end-of-life (EoL). As shown in Figure 3, the operation phase is the dominant contributor to the total impact in most categories, followed by manufacturing. The EoL phase, by contrast, presents a marginal contribution.



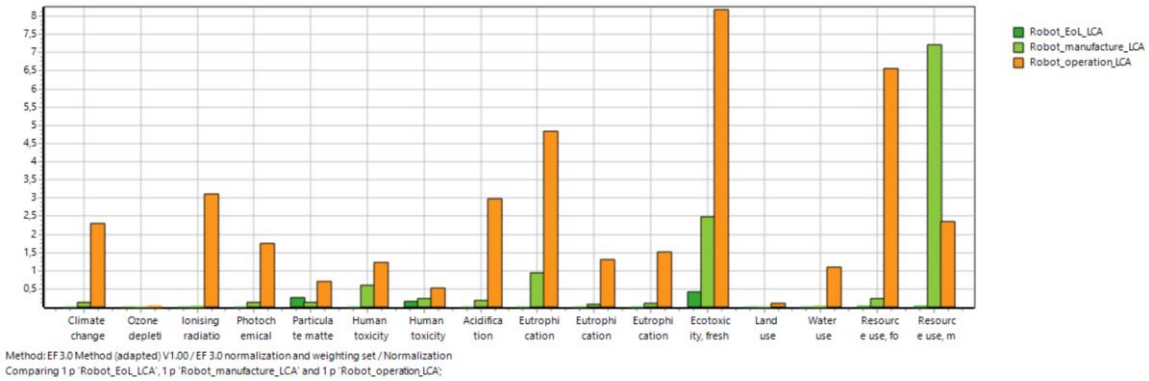


Figure 1.3. Relative contribution of each life cycle stage to the total environmental impacts of the robotic platform (manufacturing, operation and end-of-life).

The high contribution of the operation phase is primarily linked to electricity consumption, as the robot is designed to monitor 900 m² per hour and operates daily, resulting in a significant cumulative energy demand over its 10-year lifetime. This is especially visible in categories such as climate change, resource use (fossils), and acidification.

The manufacturing stage also plays an important role, particularly in categories related to materials, such as resource use (minerals and metals), ecotoxicity, and water use. This impact stems from the large number of components integrated into the robotic platform, including a steel frame, battery pack, and the full suite of onboard electronics.

Figure 1.4 shows the contribution of each sub-component of the robotic platform to the total environmental impact, based on single score values. The most significant contributor is the generic electronics subsystem, followed by the aluminum parts, battery pack, onboard computer, and sensor suite. The high impact of the electronics is particularly evident in the resource use (minerals and metals) category, due to the presence of rare earths and critical raw materials. The aluminum components and sensors also show substantial contributions, driven by their material intensity and embedded electronics. While other components such as screws, wheels, or the slip ring have a minor influence overall, the steel frame and mechanical structure still contribute notably in categories like land use and acidification. These results underscore the importance of material choices—particularly in electronics and lightweight metals—in shaping the environmental profile of the robotic system.

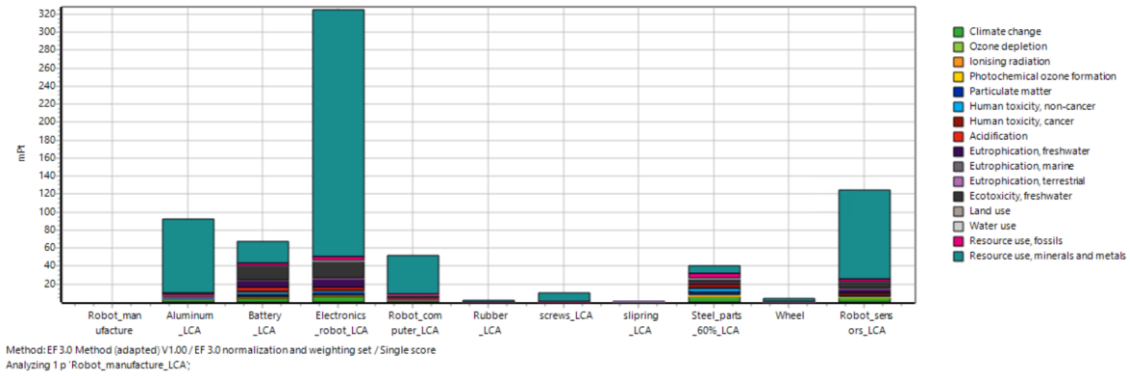


Figure 1.4. Contribution of each sub-component of the robotic platform to the impact categories (Single score, per impact category).

Normalized results presented in Figure 6 further confirm that the most significant environmental impact category is resource use, minerals and metals, followed by ecotoxicity (freshwater) and acidification. The first is primarily driven by the battery and electronics, which all contain rare earths, copper, and other high-impact materials. Ecotoxicity and acidification impacts are strongly associated with upstream supply chains for metals and electronics.

Other categories such as climate change and fossil resource use are also relevant, especially due to electricity consumption during operation. Impacts in water use, land use, or human toxicity (cancer and non-cancer) are present, but remain secondary in the normalized impact profile.

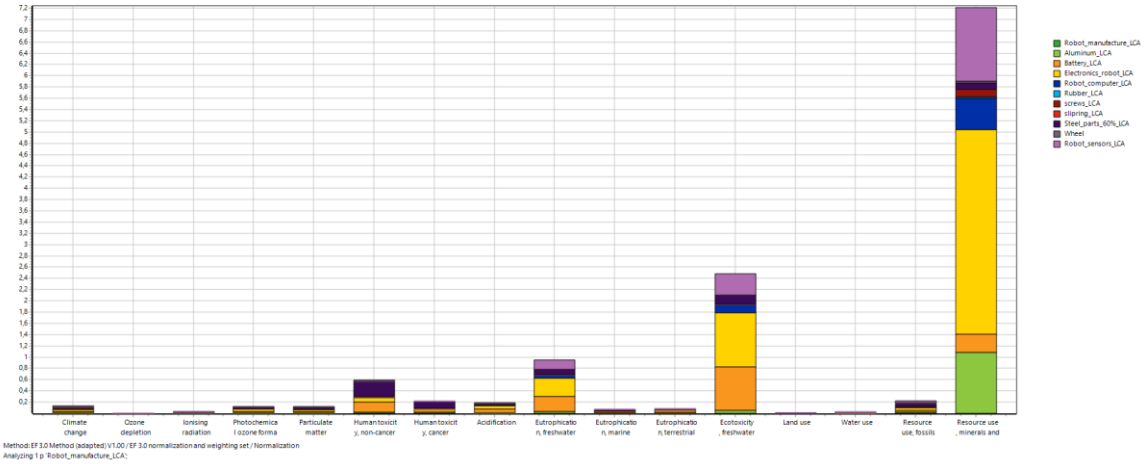


Figure 1.5. Normalized environmental impact of the robot per impact category (EF 3.0 Method).

1.3.2.3 Detailed impact results: fixed sensor mesh

The environmental impacts of the fixed-sensor mesh system were assessed across its three main life cycle phases: manufacturing, operation, and end-of-life (EoL). The EoL phase was included in the model and accounted for using standard assumptions (98% disassembly, 2% disposal). However, its contribution to the overall environmental impact proved negligible in comparison to the manufacturing and, especially, the operation phases.

As shown in Figure 6, the operation phase is by far the most significant contributor to the total environmental impact of the sensor mesh system. This is largely due to the continuous electricity consumption required to power the sensor network over the entire 10-year monitoring period. This constant energy demand results in high impacts in energy-intensive categories such as climate change, resource use (fossils), and acidification.

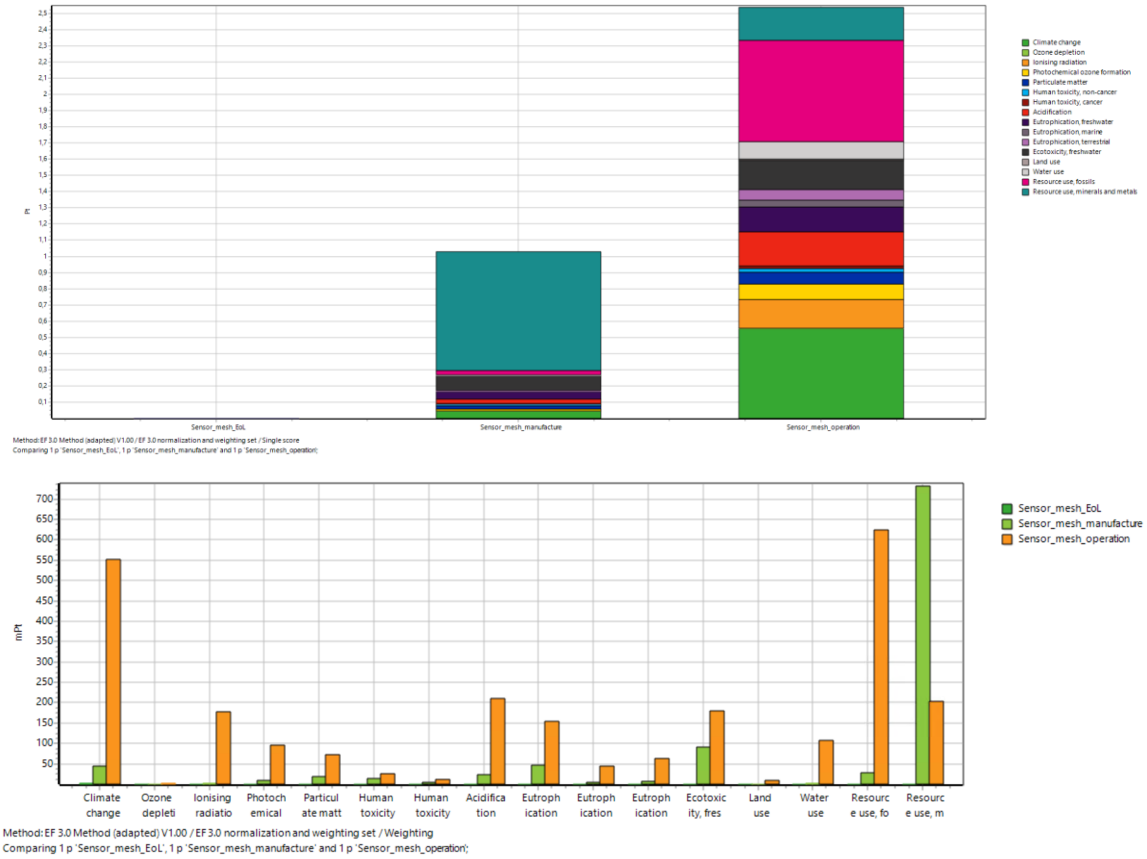


Figure 1.6. Contribution of the manufacturing and operation phases to the total environmental impact of the fixed-sensor mesh system (top: single score; bottom: weighted results, EF 3.0 method).

Figure 1.7 provides a detailed breakdown of the contribution of each component within the sensor mesh system to the 16 environmental impact categories. The electricity consumption dominates nearly all indicators, particularly climate change, photochemical ozone formation, acidification, and the three eutrophication categories.

Additionally, the NDVI, RGBD, and thermal cameras contribute significantly to toxicity-related indicators such as human toxicity (cancer and non-cancer) and ecotoxicity (freshwater), due to the use of metals, electronics and manufacturing processes with hazardous emissions. Notably, the NDVI sensor and thermal camera show relevant contributions in ionising radiation and particulate matter, driven by upstream supply chains involving electronics and coated optical materials.

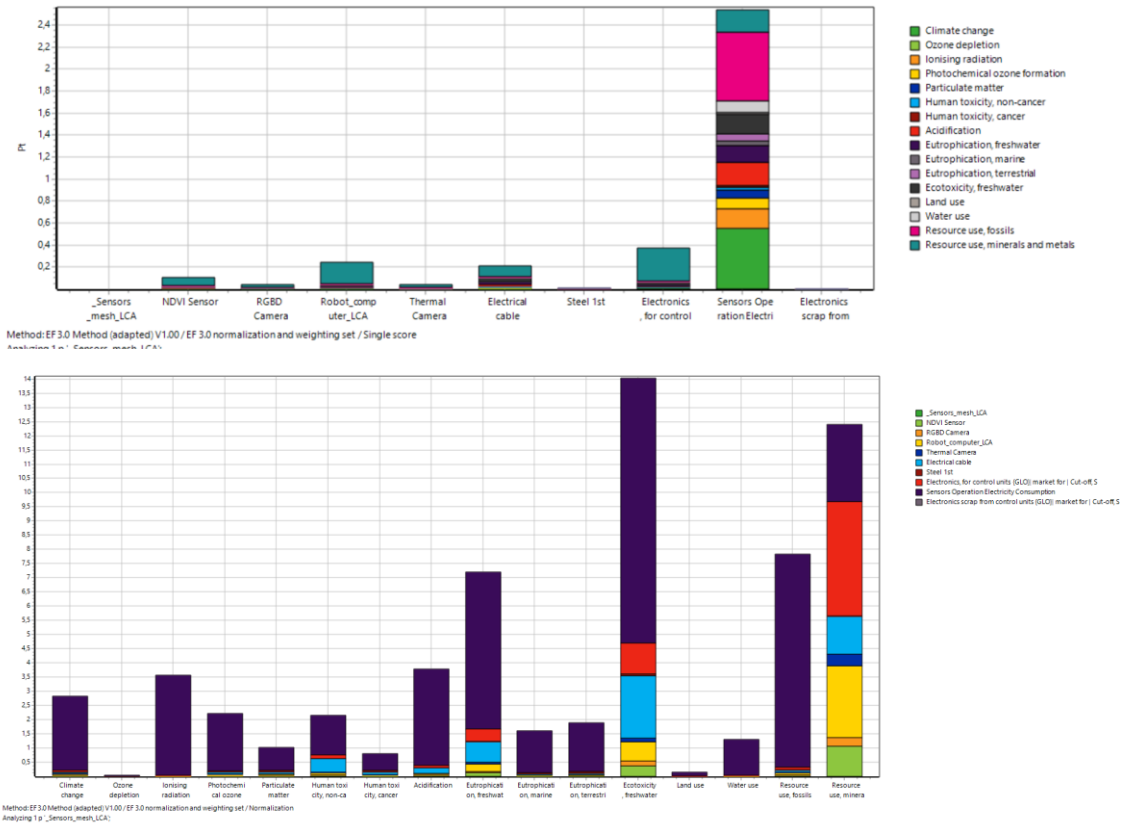


Figure 1.7. Contribution of each component of the sensor mesh system to the 16 environmental impact categories (top: single score; bottom: normalization results, EF 3.0 method).

Figure 1.8 illustrates the contribution of individual components to the environmental impact of the sensor mesh manufacturing stage. Both the single score and weighted results confirm a strong dominance of the resource use (minerals and metals) category, primarily driven by the electronics used in control units and computing elements, such as the onboard computer and communication electronics. These subsystems contain rare earths, critical metals, and complex microelectronic structures that significantly affect the impact in this category.

Electrical cables also contribute substantially to several impact categories, including freshwater ecotoxicity, acidification, and resource use (fossils), due to their metal content (e.g., copper) and the energy-intensive processes involved in their production. In addition, thermal and RGBD cameras, while smaller in mass, add noticeable shares in categories such as human toxicity and ionising radiation, reflecting the embedded burden of their electronic components and sensor optics.

Overall, although the fixed-sensor mesh is composed of relatively simple components, the cumulative impact of electronics and cabling is considerable. These findings highlight that, in addition to operational electricity consumption, the embedded material intensity of the sensor hardware — particularly in control and communication elements — plays a central role in shaping the overall environmental profile.

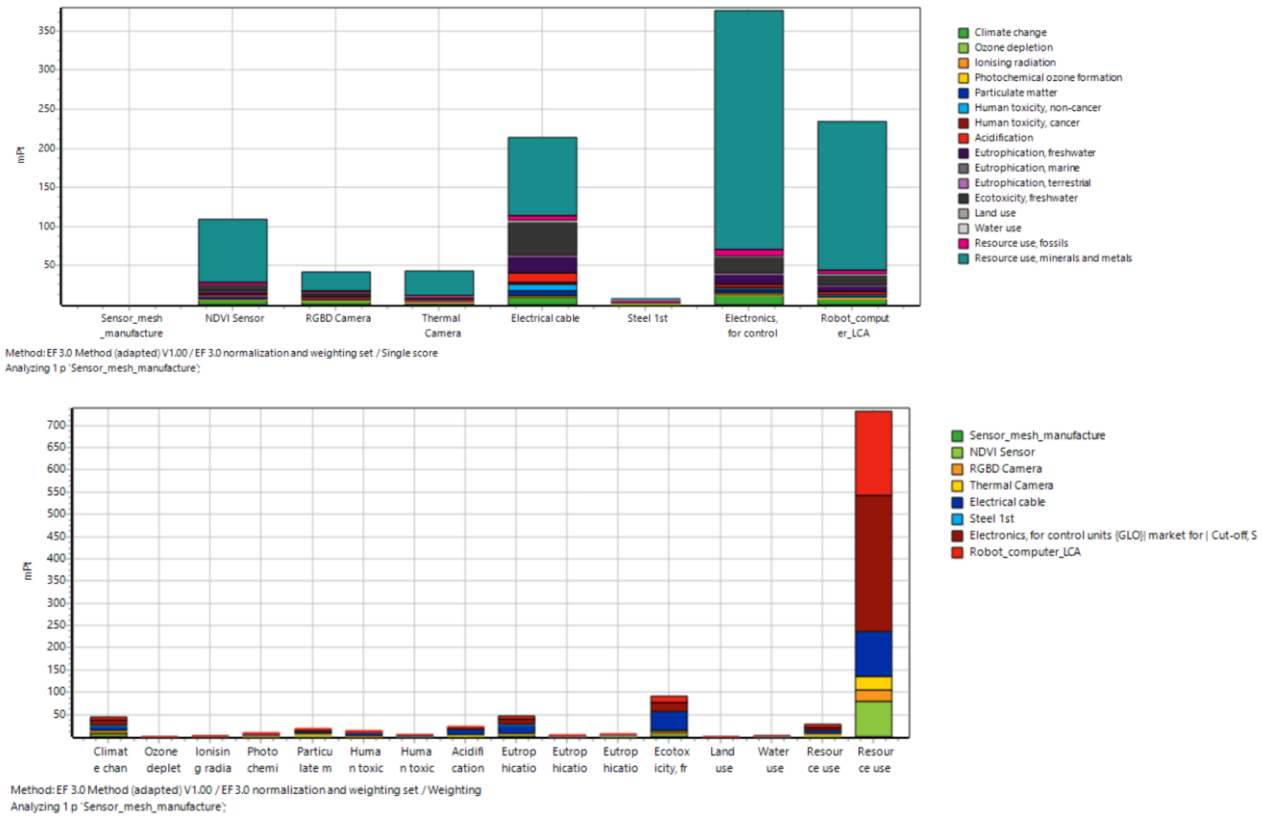


Figure 1.8. Environmental impact of manufacturing the fixed-sensor mesh system per components (top: single score; bottom: weighting, EF 3.0 method).

1.3.2.4 *Comparative analysis: robotic system vs. fixed-sensor mesh*

This section presents a comparative assessment of the two monitoring strategies analyzed in the SYMBIOSYST project: the autonomous robotic platform and the fixed-sensor mesh. Both systems are designed to deliver equivalent spatial and temporal monitoring coverage over a reference area of 900 m² and a 10-year period, but they differ substantially in design, material complexity, and operational profiles.

Figure 9 shows the aggregated single-score results of both systems, weighted across all impact categories. The sensor mesh presents a slightly higher overall environmental impact than the robotic platform. This difference is largely driven by its continuous energy consumption over time, which accumulates significantly in categories such as climate change and resource use (fossils). In contrast, the robot's impacts are more concentrated in the manufacturing phase and are linked to the presence of materials with high embedded impacts, such as lithium-ion batteries, electronics, and structural metals.

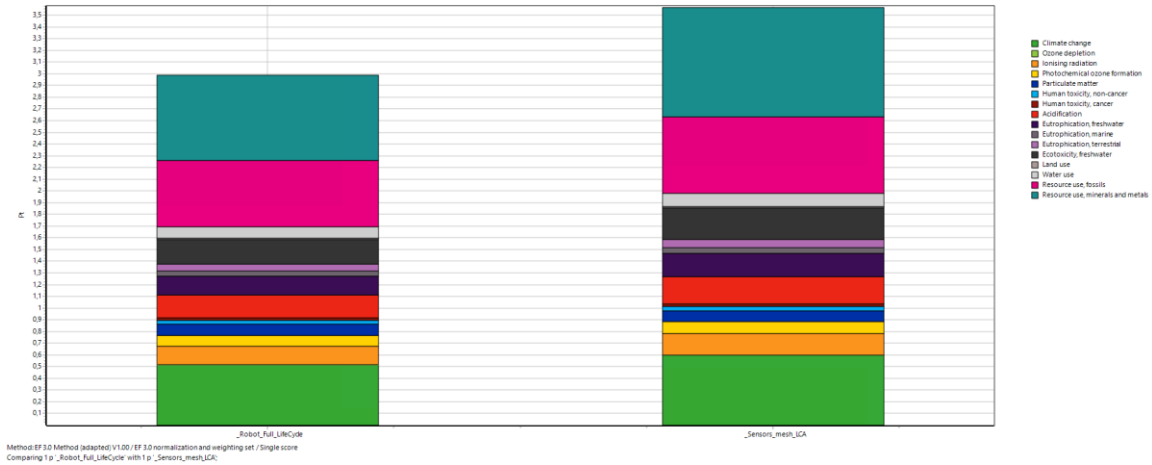


Figure 1.9. Absolute single score comparison of total environmental impacts between the robotic platform and the fixed-sensor mesh system (EF 3.0 Method)

Figure 1.10 illustrates the normalized environmental performance across the 16 EF 3.0 impact categories. The sensor mesh performs worse in most categories when normalized per functional unit. It shows clearly higher impacts in resource use (fossils), climate change, eutrophication (freshwater and terrestrial), acidification, and ecotoxicity. This highlights the strong influence of electricity consumption during its entire operational

lifetime. The robotic platform, despite its high material complexity, shows relatively lower impacts in the same categories. However, it still contributes substantially to indicators such as resource use (minerals and metals) and human toxicity (cancer and non-cancer), driven by its embedded electronics and sensors.

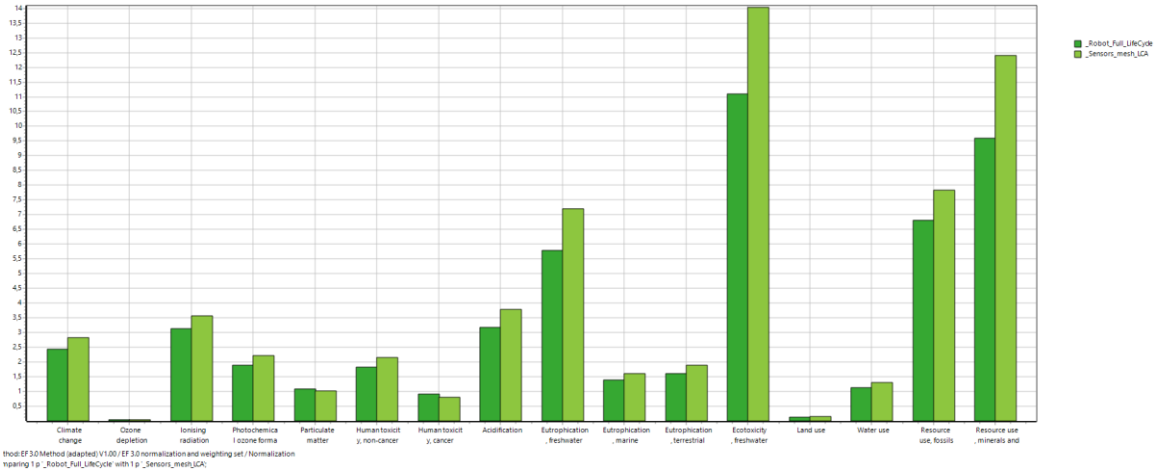


Figure 1.10. Normalized environmental impacts of the robotic platform and fixed-sensor mesh system across impact categories (EF 3.0 Method).

Figure 1.11 provides a percentage breakdown of each system's relative contribution per impact category. The fixed-sensor mesh dominates in categories linked to cumulative energy use, such as climate change, resource use, fossils and eutrophication. On the other hand, the robotic platform contributes more significantly to

resource use (minerals and metals), land use, and toxicity-related categories, reflecting the burden of its upfront material composition.
These findings underline a fundamental trade-off:

- The robot concentrates its environmental footprint in the manufacturing stage, with higher upfront impacts but less intense long-term energy consumption.

- The sensor mesh spreads its environmental burden over time, driven by constant energy usage, which may become increasingly significant depending on the electricity mix used in the future.

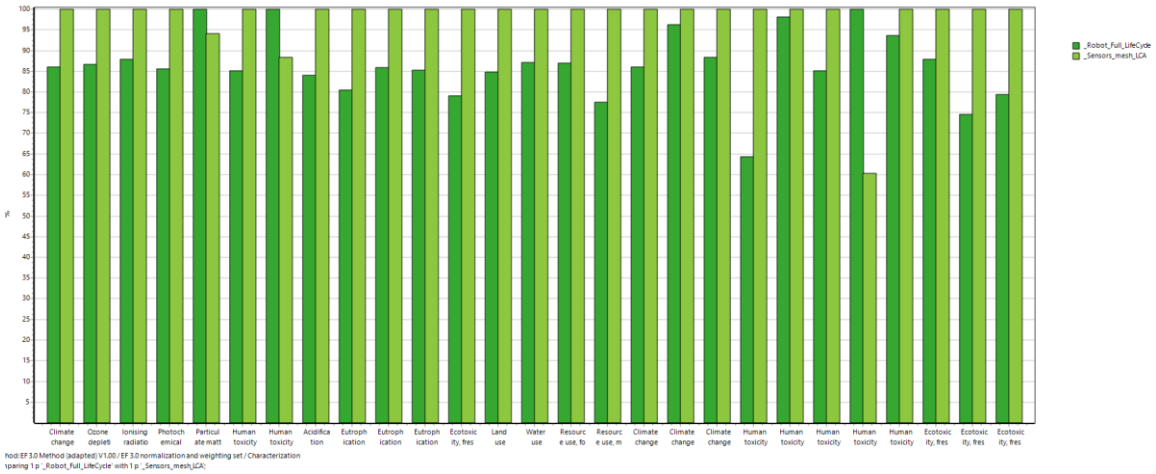


Figure 1.11. Relative contribution (%) of the robotic platform and fixed-sensor mesh system to each impact category (characterization results, EF 3.0 Method)

1.3.2.5 *SENSITIVITY ANALYSIS: EFFECT OF SENSOR DENSITY ON THE ENVIRONMENTAL PERFORMANCE OF THE FIXED-SENSOR MESH*

One of the key variables influencing the environmental footprint of the fixed-sensor mesh system is the spatial density of the sensors deployed in the field. Since each sensor set provides data for a fixed surface area, increasing or decreasing the resolution (i.e., sensors per square meter) has a direct impact on the total number of devices required—and therefore on the environmental impacts associated with manufacturing, operation, and end-of-life.

In the base scenario, one sensor set is used for every 50 m² of monitored field (i.e., 18 sensor sets for 900 m²). To evaluate the robustness of this assumption, two additional scenarios were explored:

- Low-density scenario (1 sensor set per 100 m²): Reduces the total number of sets needed to 9.

- High-density scenario (1 sensor set per 25 m²): Increases the total number of sets to 36.

Figure 12 presents the environmental impacts of the high-density fixed-sensor mesh scenario (1 set per 25 m²), compared to the robotic platform. In terms of absolute single score (EF 3.0 method), it is evident that increasing the sensor density significantly amplifies the overall environmental burden of the mesh system. This is primarily due to the multiplication of materials, embedded electronics, and associated electricity

consumption. In this configuration, the total impact of the sensor mesh surpasses that of the robot by a substantial margin.

Figure 13 shows the results for the low-density scenario (1 set per 100 m²), again in comparison with the robotic platform. In this case, the total environmental burden is significantly reduced, with impacts falling below those of the robot in most categories. The lower number of sensor units results in proportionally less material and energy demand, improving performance in key indicators such as climate change, resource use (minerals and metals), and ecotoxicity.

Together, these figures highlight the critical influence of sensor deployment density on the overall environmental performance of the monitoring system. While higher sensor resolution may improve data granularity, it also imposes a much higher environmental cost. Conversely, reducing the density can enhance sustainability but may affect the spatial coverage and precision of agronomic data. This trade-off should be carefully balanced in future system design and deployment decisions.

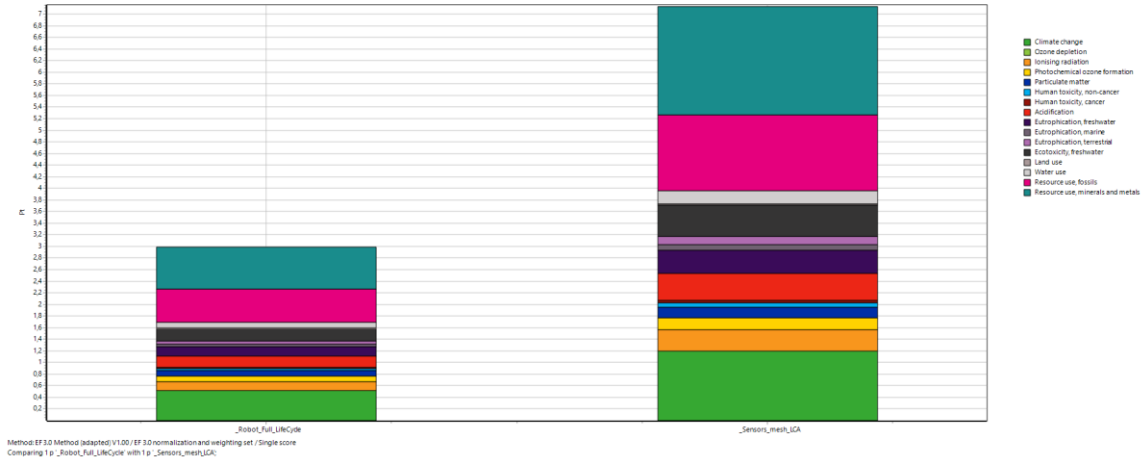


Figure 1.12. Environmental impact of the fixed-sensor mesh system with high sensor density (1 set per 25 m²) compared to the robotic platform (EF 3.0 Method, single score).

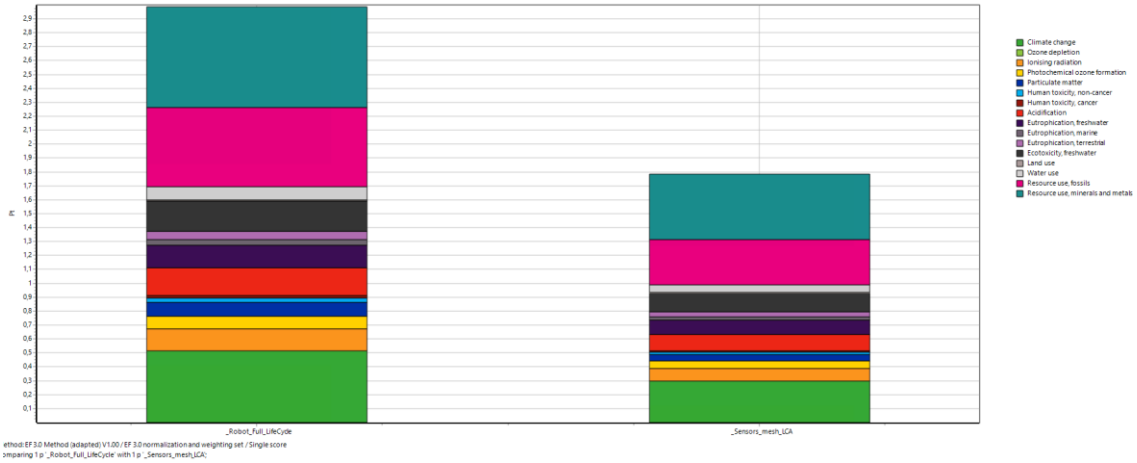


Figure 1.13. Environmental impact of the fixed-sensor mesh system with low sensor density (1 set per 100 m²) compared to the robotic platform (EF 3.0 Method, single score).

1.3.2.6 *DISCUSSIONS*

This comparative Life Cycle Assessment (LCA) provides a detailed and data-driven evaluation of two realistic monitoring strategies for agrivoltaic systems: a mobile robotic platform and a fixed-sensor mesh. Rather than pointing to a single optimal solution, the results highlight how design assumptions, deployment strategies, and functional capabilities shape the environmental profile of each system.

Granularity vs. continuity

One of the key trade-offs between both approaches lies in how they collect data over time and space. The fixed-sensor mesh offers continuous temporal monitoring from specific fixed locations, allowing near real-time observations. However, this requires extrapolating data from discrete points, assuming homogeneity within subplots — an assumption that may not hold under diverse or heterogeneous crop conditions. Moreover, achieving dense spatial coverage increases the number of sensors significantly, leading to high material intensity and energy consumption.

In contrast, the robotic platform provides high spatial resolution, capturing plant-by-plant measurements without requiring extrapolation. This enhances precision and allows for site-specific insights, enabling more accurate diagnoses and tailored agronomic decisions. Although the robot operates at a lower temporal frequency, the richness and granularity of the data make it particularly suitable for applications where per-plant detail is critical.

Environmental trade-offs and system versatility

From an environmental perspective, the robot and the mesh show comparable total impacts, especially when the mesh is deployed at moderate density (e.g., one set per 50 m^2). At higher densities (25 m^2), the sensor mesh becomes significantly more impactful than the robot. At lower densities (100 m^2), the mesh becomes the most efficient solution — but possibly at the cost of under-sampling.

However, beyond the LCA indicators, the robotic platform demonstrates several strategic advantages:

- It is multifunctional by design, able to support additional agricultural tasks such as spraying, mapping, transport, or manipulation. This allows the environmental impact to be shared across multiple functions in future applications.

- Only one sensor set is required, which opens the door to using higher-quality, more expensive sensors that would be infeasible to deploy in large quantities across a field.

- Its centralized maintenance, ease of deployment, and rapid reconfiguration reduce installation time, infrastructure complexity, and labour intensity compared to deploying dozens of fixed nodes.

- It supports adaptive interventions, enabling real-time action in response to plant-level anomalies, which is not feasible with static monitoring setups.

These benefits position the robot as a versatile, scalable, and precision-oriented solution for agrivoltaic contexts — particularly valuable in dynamic or high-value cropping systems.

1.3.2.7 *LIMITATIONS AND FUTURE WORK*

This study intentionally focused on the core elements of each system, with some assumptions that simplify real-world deployment:

- Installation and maintenance requirements of the sensor mesh were not included but are expected to be non-negligible, especially in large installations.
- Sensor failures, calibration needs, and replacements may be more frequent in fixed systems exposed continuously to environmental stressors.
- Cost, labour, and usability were not analysed, though they strongly influence adoption.
- Energy source scenarios, such as solar-powered sensors or off-grid charging for robots, were not modelled but represent viable mitigation pathways.

Future work should address these aspects, expand the analysis with real usage data, and consider hybrid architectures that combine the strengths of both systems.

1.4 FINAL REFLECTIONS

This study highlights how monitoring design is a strategic choice, involving trade-offs between spatial and temporal resolution, system flexibility, and environmental performance. The robotic platform, although not universally superior, stands out for its capacity to provide detailed, per-plant data, reduce field infrastructure, and support multiple functions. Meanwhile, the sensor mesh remains a scalable and efficient solution under certain deployment assumptions — especially if energy use is minimized and density carefully optimized.

Ultimately, the most sustainable and effective strategy may emerge from combining both approaches, adapting each to specific crop needs, field conditions, and operational constraints in agrivoltaic systems.

REFERENCES

[1] Müller, A.; Friedrich, L.; Reichel, C.; Herceg, S.; Mittag, M.; Neuhaus, D. H. A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory, *Solar Energy Materials and Solar Cells, 2021,* 230, 111277.