ASSESSING SUSTAINABILITY AND CIRCULARITY IN AGRIVOLTAIC SYSTEMS: BACKGROUND AND FUTURE WORK

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ABSTRACT: Agrivoltaic systems (AVS) co-locate photovoltaic (PV) electricity generation and agricultural production on the same land parcel. While their technical potential is increasingly recognized, the sustainability and circularity of their support structures remain underexplored. The objective of this work is to assess the sustainability of these elements, trough aspects of circularity, environment and costs. To this end, the Integrated Value Model for Sustainability Assessment (MIVES) is applied to compare two material alternatives—galvanized steel and structural timber—for an elevated, single-axis AVS support structure designed to carry 28m^2 of PV modules. The decision model includes social, environmental and circularity requirements, 7 criteria and 24 indicators. Results show that timber achieves a substantially higher sustainability index (0,63) than steel (0,32) under the baseline weighting, driven by lower environmental burdens, reduced dependence on non-renewable resources and favorable end of life options. A sensitivity analysis, varying requirement weights, confirms the selection of timber as the most sustainable alternative. The study demonstrates how MIVES can integrate circularity and sustainability into design decisions for AVS and identifies priorities for future methodological development and data refinement.

Keywords: Agrivoltaics, AgriPV, Sustainability, Circular Economy, MIVES

1 INTRODUCTION

Agrivoltaic systems (AVS) or AgriPV, combine photovoltaic (PV) power generation with agricultural activities on the same land parcel, enabling dual use for energy and food production. The concept traces back to Goetzberger and Zastrow, who proposed elevated PV collectors that allow continued plant cultivation beneath the modules [1]. Subsequent studies and reviews have confirmed that AVS can enhance land use efficiency and, under suitable design, maintain or improve crop yields while producing electricity [2], [3]. The European Union's solar and climate strategies foresee a massive expansion of PV capacity by 2030, and recent analyses suggest that deploying AVS on a small share of agricultural land could contribute substantially to these targets [3], [4].

AVS are typically conformed by four main elements: (i) PV modules and electric balance of system (BOS); (ii) support structures; (iii) agricultural component; (iv) site-specific interfaces such as fencing. Technical reviews and project reports emphasize that support structures are central to AVS performance because they determine clearance height, shading patterns, microclimate and machinery accessibility, while also contributing significantly to embodied impacts and costs [2], [3], [5].

Research on AVS sustainability has so far focused primarily on land use efficiency, crop yields, water use and energy performance at the system level [2], [3]. Life cycle assessment (LCA) has been widely applied to PV systems and, increasingly to AVS, but few studies explicitly isolate or optimize the structural subsystem despite its relevance for material use and environmental impacts [6], [7].

Circularity adds a consideration by focusing on material loops, design for disassembly, durability, reparability and end of life strategies such as reuse or recycling. Frameworks such as Ellen McArthur Foundation's circularity indicators and related taxonomies demonstrate how these aspects can be quantified for products and structures [8], [9].

Policy-oriented reports on AVS in the European Union stress the need for harmonized definitions, standards and evaluation methods to support coherent regulation and investment [4]. The objective of this work is to assess the sustainability of these elements, trough aspects of circularity, environment and costs by applying a multicriteria decision making (MCDM) model called MIVES. This methodology have been applied in architecture and civil engineering to integrate economic, environmental and social dimensions into single sustainability indices and to compare design alternatives[10]. In this context, MIVES offers a way to combine economic, environmental and circularity indicators into a coherent assessment thereby contributing to foundations needed for evidence based AVS deployment.

2 METHODOLOGY

2.1 Model for sustainability assessment

MIVES is based on a hierarchical tree that decomposes a decision problem into requirements, criteria and indicators, and uses value functions to convert heterogeneous indicator values into dimensionless indices between 0 and 1, which can then be aggregated into a single sustainability index [10]. In this study, MIVES was implemented following the version 2.1.1 released in October 2016.

Key steps in the methodology includes:

a. Definition of system limits
b. Construction of decision tree
c. Indicator quantification
d. Application of value functions
e. Aggregation and sustainability index

2.2 Case study

The case study is based on an elevated, single-axis AVS structure related to the SYMBIOSYST Project, calculations, inventory analysis and assessment were carried out by GRIC [5]. Table I, present the elements relative to the initial model conditions.

Table I. MIVES assessment considerations

Element	Description
Functional unit	A support structure capable of carrying 28m^2 of PV modules
Boundaries	Cradle to grave
Inventory sources	Costs data, Ecoinvent 3.6
Impact assessment method	EF 3.0 method [11]

The assessed structural section is shown in Figure 1. The two material alternatives are steel and timber. For the steel option, galvanized carbon steel with zinc coating for foundations and the tube and module support system was considered. In the case of the timber alternative, structural softwood (German pine) with autoclave treatment was analyzed. Secondary components such as fasteners, rotation mechanisms, aluminum parts and stainless-steel elements remained unchanged for both material alternative scenarios. The total mass of steel structure was 625kg, whereas the timber option had a total of 351kg.

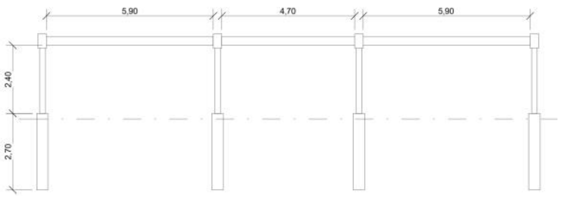

Fig.1 Structural section analyzed.

The common section is composed by 4 driven steel piles anchoring columns (2,7m), 4 columns (2,4m) and 3 beams (5,90m; 4,70m; 5,9m), forming 3 portal frames.

2.3 MIVES decision tree

The decision tree comprises 3 requirements (R1-R3), 7 criteria (C1-C7) and 27 indicators (I1-I24). Figure 2 presents the model tree and the relative value for each element.

All indicators were converted to value indices using linear functions, with decreasing functions for burdens (e.g. impacts, costs, virgin material share, irrecoverable waste) and increasing function for benefits (e.g. resource duration, utility, recycled material share).

Weights follow 3 principles: (1) equal weight for indicators within each criterion; (ii) criteria weights proportional to their number of indicators; and (iii) equal weight for environmental and circularity requirements (44,5%), with a smaller weight for the economic requirement (10%) for the baseline scenario. Five additional weighting scenarios are defined for the sensitivity analysis in Table II.

Table II. Sensitivity analysis weighting scenarios (%)

Scenario	Economic	Environmental	Circularity
S1	33	33	33
S2	5	30	65
S3	30	65	5
S4	65	5	30
S5	8	67	25

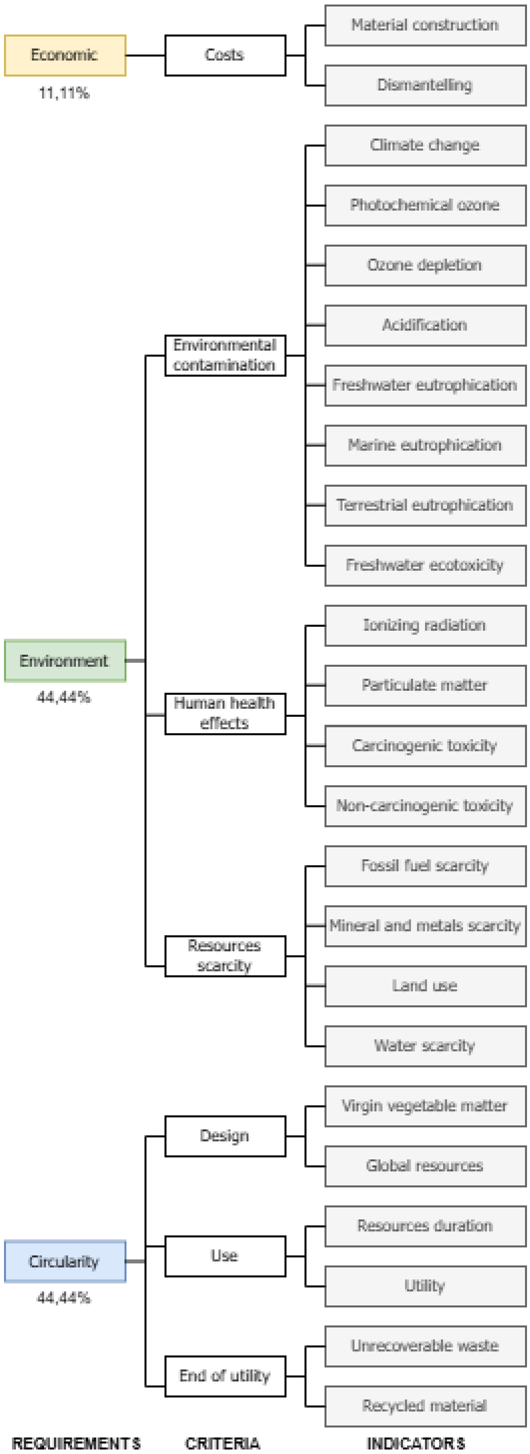

Fig. 2. Decision tree for the case study.

3 RESULTS

3.1 Main results

Figure 3 shows the global sustainability index for the baseline model scenario. For most environmental indicators (I3–I16, I18), timber displays substantially lower burdens than steel; for example, climate change impacts decrease from 928 to 408 kg CO_2 eq, fossil resource scarcity from 12425 to 5566 MJ, and freshwater ecotoxicity from 40969 to 14870 CTUe. Timber also exhibits lower water scarcity (114 vs. 300 m^3 depriv.) and a lower share of virgin raw material (0,30 vs. 0,71), as well as a more favorable global resource indicator (0,34 vs. 0,97).

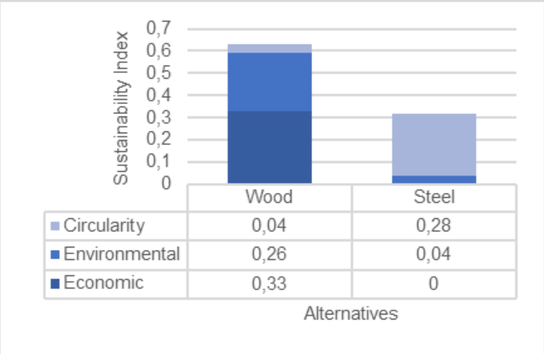

Fig. 3. Global sustainability index.

The economic criterion C1 shows very similar construction costs for both alternatives (approximately 2600 EUR), but dismantling costs are significantly lower for timber (21,5 vs. 59,6 EUR), yielding a much higher economic value index for timber.

For the environmental requirement R2, timber achieves higher value indices across pollution (C2), human health (C3) and resource scarcity (C4), reflecting the lower LCA impacts associated with lower mass, lower energy intensity of production and the carbon-storage function of wood under the assumed LCA modelling choices.

Regarding circularity (R3), both materials perform relatively well. Still, timber has an advantage in design (C5) due to lower virgin raw material use and better global resource performance, and a slightly higher value index for irrecoverable waste (I23). In contrast, steel performs strongly in recycled fraction (I24). Overall, circularity indices C5–C7 and R3 are higher for timber, with C7 (end of life) being similar for both materials.

In sum, the global sustainability index of timber alternative (0,63) has achieved a better result than the steel option (0,32).

3.2 Sensitivity analysis

Figure 4 shows the sensitivity analysis results according to the weighting distribution mentioned on Table II.

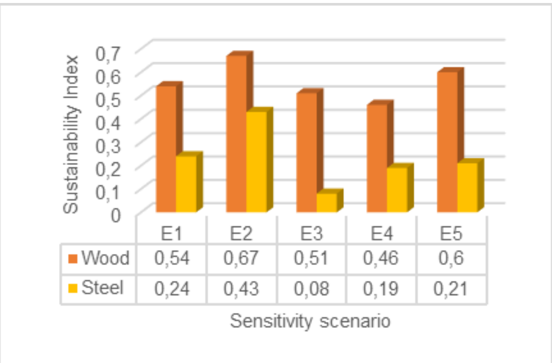

Fig. 4. Sensitivity analysis results.

In all scenarios, timber remains the more sustainable alternative. The performance gap is largest in scenarios that emphasize environmental and circularity aspects (E2 and E3) but persists even when economic aspects dominate (E4). This confirms that the ranking is not a result of a particular weighting configuration.

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion of results

The analysis indicates that, for the AVS support structure considered, structural timber outperforms galvanized steel in terms of the integrated sustainability index across all weighting scenarios. Several drivers can be identified:

(i) Environmental benefits: Timber shows systematically lower environmental burdens across climate change, eutrophication, toxicity and resource depletion indicators, owing to lower material mass, lower energy intensity of production and the role of wood in carbon storage under the adopted LCA assumptions.

(ii) Economic performance: Construction costs are similar, but dismantling costs are substantially lower for timber, leading to a higher economic value index even when the economic requirement receives a relatively high weight.

(iii) Circularity performance: Timber uses a lower share of virgin material and exhibits a lower fraction of irrecoverable waste, while maintaining a high recycled fraction; steel benefits from well-established recycling routes but remains more dependent on primary metal inputs.

These results are consistent with broader LCA and circularity discussions on material choice for structural components and their role in environmental and resource footprints[8], [11], [12].The sensitivity analysis further shows that improving circularity does not necessarily conflict with economic performance; timber remains preferable in scenarios that emphasize costs, suggesting that higher circularity and lower environmental impacts can be achieved without sacrificing economic value in this case.

The study nonetheless has several limitations. It considers a single structural section and project configuration; different geometries, spans, loading conditions or design codes could alter the relative performance of materials [6], [9], [12]. Social aspects are not included, as the social requirement was judged more appropriate at system level rather than for a subsystem such as the structure. Economic indicators are restricted to construction and dismantling costs; operation, maintenance and revenue effects are outside the scope. Finally, some LCA and circularity data derive from project-specific inventories and assumptions that may evolve as the SYMBIOSYST project progresses.

4.2 Conclusions and future work

This work has presented a MIVES-based assessment of sustainability and circularity for AVS support structures, comparing galvanized steel and timber alternatives for an elevated single-axis structure supporting 28 m^2 of PV modules. The main conclusions are:

(i) Timber exhibits a higher overall sustainability index than steel in the baseline scenario (0,63 vs. 0,32) and in all five alternative weighting scenarios, driven by better performance in economic, environmental and circularity requirements.

(ii) Circularity indicators materially influence the ranking of alternatives, highlighting the importance of design, use and end of life aspects in addition to environmental impacts and costs when selecting materials for AVS structures.

(iii) MIVES proves to be a suitable framework for assessing AVS structures, enabling transparent integration of LCA-derived indicators and circularity metrics into a single index that can accommodate different stakeholder preferences via sensitivity analyses.

Future work could build on this study in several directions:

(i) Broader design space: Extending the comparison to additional AVS structural typologies and hybrid solutions (e.g. steel–timber combinations, bio-based composites) to test the generality of the findings.

(ii) Refined circularity metrics: Further developing and harmonizing circularity indicators for AVS structures, including more detailed modelling of reuse, cascading and long-term material flows.

(iii) Integration of social and system level economic aspects: Incorporating social indicators and project-level economic metrics (e.g. levelized cost of electricity, farm income effects, participatory dynamics, landscape impacts and co-benefits) into MIVES models to support integrated AVS decision-making.

(iv) Improved data quality and scenario analysis: Enhancing LCA and circularity data with more detailed, region-specific inventories and exploring material durability and replacement scenarios under varying climatic and operational conditions. This includes the complementary use of other sustainability assessment methodologies such as LCA for costs, environmental and social impacts regarding the entire elements of AVS.

By including circularity within sustainability assessment for AVS structures, such work can contribute to more resource efficient, climate aligned and socially robust deployment of agrivoltaics in support of the energy transition.

5 REFERENCES

[1] A. Goetzberger and A. Zastrow, "On the Coexistence of Solar-Energy Conversion and Plant Cultivation," *Int. J. Sol. Energy*, vol. 1, no. 1, pp. 55–69, Jan. 1982, doi: 10.1080/01425918208909875.

[2] A. Ghosh, "Nexus between agriculture and photovoltaics (agrivoltaics, agriphotovoltaics) for sustainable development goal: A review," *Sol. Energy*, vol. 266, p. 112146, Dec. 2023, doi: 10.1016/j.solener.2023.112146.

[3] G. Pandey, S. Lyden, E. Franklin, B. Millar, and M. T. Harrison, "A systematic review of agrivoltaics: productivity, profitability, and environmental co-benefits," *Sustain. Prod. Consum.*, vol. 56, pp. 13–36, June 2025, doi: 10.1016/j.spc.2025.03.006.

[4] A. Chatzipanagi, N. Taylor, and A. Jaeger-Waldau, "Overview of the potential and challenges for Agri-Photovoltaics in the European Union.," JRC Publications Repository. Accessed: Dec. 08, 2025. [Online].Available:https://publications.jrc.ec.europa.eu/repository/handle/JRC132879

[5] F. Nack, Torri, Giulia, Macarulla, Marcel, and Gassó-Domingo, Santiago, "Evaluación de la Sostenibilidad y Circularidad de Estructuras de Soporte en Sistemas Agro-Fotovoltaicos," July 2024, Accessed: Dec. 08, 2025. [Online]. Available: https://hdl.handle.net/2117/421407

[6] M. J. de Wild-Scholten, "A cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems," *Eur. Photovolt. Sol. Energy Conf.*, no. 21, 2006.

[7] C. S. Choi *et al.*, "Combined land use of solar infrastructure and agriculture for socioeconomic and environmental co-benefits in the tropics," *Renew. Sustain. Energy Rev.*, vol. 151, p. 111610, Nov. 2021, doi: 10.1016/j.rser.2021.111610.

[8] J. Goddin, K. Marshall, A. Pereira, and C. Tuppen, "Circularity Indicators: An Approach to Measuring Circularity, Methodology," Ellen McArthur Foundation. Accessed: Dec. 08, 2025. [Online]. Available: https://www.researchgate.net/publication/353687971_Circularity_Indicators_An_Approach_to_Measuring_Circularity_Methodology

[9] E. Franklin-Johnson, F. Figge, and L. Canning, "Resource duration as a managerial indicator for Circular Economy performance," *J. Clean. Prod.*, vol. 133, pp. 589–598, Oct. 2016, doi: 10.1016/j.jclepro.2016.05.023.

[10] O. Pons, A. De la Fuente, and A. Aguado, "The Use of MIVES as a Sustainability Assessment MCDM Method for Architecture and Civil Engineering Applications," *Sustainability*, vol. 8, no. 5, p. 460, May 2016, doi: 10.3390/su8050460.

[11] S. Fazio, F. Biganzoli, L. V. De, L. Zampori, S. Sala, and E. Diaconu, "Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods," JRC Publications Repository. Accessed: Dec. 08, 2025. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC114822

[12] R. Roy and J. M. Pearce, "Is small or big solar better for the environment? Comparative life cycle assessment of solar photovoltaic rooftop vs. ground-mounted systems," *Int. J. Life Cycle Assess.*, vol. 29, no. 3, pp. 516–536, Mar. 2024, doi: 10.1007/s11367-023-02254-x.

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