DELIVERABLE REPORT

D5.2 – Policy advisory report MCDA for eco design and sustainability roadmap of the most sustainable PVSK/Si tandem modules (incl. analysis from LCC, LCA, social LCA, and recycling protocols).

Deliverable D5.2
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PREPARED BY
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NEXUS is a 3-year research and innovation project funded by the European Commission through the Horizon Europe Research and Innovation Action (RIA) grant N°101075330, responding to the call for a "*Sustainable, secure and competitive energy supply*" (HORIZON-CL5-2021-D3-02).

NEXUS aims to accelerate Europe's energy transition by developing perovskite-silicon tandem photovoltaic technology, via a new European paradigm: an eco-design approach, based on efficiency, cost, sustainability, circularity and social aspects and using abundant materials. NEXUS aims to develop stable, 2-terminal perovskite-silicon tandem solar cells and modules with high power conversion efficiencies, using sustainable, coherent and competitive European PV production, to create a viable economic pathway for the European commercialisation of this technology.

NEXUS is formed of a multi-disciplinary consortium: 12 partners from 9 European countries; 5 industrial partners & 7 RTOs, covering the whole value chain of innovation from research centres to technology providers, end-users and market and policies.

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NEXUS Consortium

Organization name	Short name	Country
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA	FR
ACCADEMIA EUROPEA DI BOLZANO	EURAC	IT
KARLSRUHER INSTITUT FUER TECHNOLOGIE	KIT	DE
RIJKSUNIVERSITEIT GRONINGEN	RUG	NL
SALD B.V	SALD	NL
UNIVERSITAT DE VALENCIA	UVEG	ES
ENEL GREEN POWER SPA	EGP	IT
ICARES CONSULTING	BI	BE
NORSUN AS	NORSUN	NO
THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD	UOXF	UK
OXFORD PHOTOVOLTAICS LIMITED	OXPV	UK
FACHHOCHSCHULE NORDWESTSCHWEIZ	FHNW	CH

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Table of Content

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List of Tables

List of Figures

Abbreviations and Acronyms List

Abbreviation	Meaning
2T	2 terminal
AZO	Aluminium zinc oxide
BS	Back sheet
C60	fullerene
CED	Cumulative energy demand
CN	China
C-Si	Crystalline silicon
CZ	Czochralsky
ECA	Electrically conductive adhesive
EF	Environmental footprint
GHG	Greenhouse gas
GHG	Greenhouse gas
GW	Giga watt
GWP	Global warming potential
HTL	Hole transfer layer
ITO	Indium tin oxide
KSI	Key sustainability indicators
kW	Kilowatt
kWh	Kilowatt hour
kWp	Kilowatt peak
LCA	Life cycle assessment
LCC	Life cycle costing
LCOE	Levelized cost of electricity
MBB	Multi wire brazing
MCDA	Multi criteria decision analysis
PST	Perovskite silicon tandem
PV	Photovoltaic
RJ	Recombination junction
SHJ	Silicon heterojunction
TCO	Transparent conductive oxide
TPO	Thermoplastic olefin

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TW	Tera watt

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1. Executive Summary

This study provides a comprehensive sustainability evaluation of the NEXUS technologies using an integrated Multi-Criteria Decision Analysis (MCDA) approach. The assessment combines environmental, technical, economic, and social criteria to compare two manufacturing configurations for the perovskite/silicon tandem technology: a baseline technology, with a China-sourced Si wafer, indium-based transparent electrodes, full-silver contacts, and an optimised NEXUS configuration, with Si sourced in Europe, without indium and with reduced silver content. Five weighting scenarios were applied to reflect different policy and stakeholders' priorities, ensuring a robust and balanced evaluation.

Across all scenarios, the NEXUS Optimised technology consistently outperforms the baseline, demonstrating higher eco-efficiency, improved environmental performance, enhanced technical readiness, and better alignment with social sustainability principles. While the Baseline system is rated as “mostly sustainable” in most scenarios, it becomes non-sustainable when economic criteria dominate. In contrast, the NEXUS configuration achieves sustainable scoring in nearly all scenarios, confirming its suitability for large-scale deployment.

The integration of circularity and social considerations into the MCDA framework reinforces the importance of holistic sustainability in next-generation PV technologies. The results highlight the significant benefits of process optimisation, improved material efficiency, and enhanced end-of-life strategies embedded within the NEXUS solution.

Beyond the quantitative evaluation, the study also identifies a set of EU Policy Levers to support the industrial uptake of sustainable PV technologies. These include:

- Mandatory Eco-design and LCA Transparency to ensure sustainability is embedded from the design phase.
- Circular Economy incentives promoting recycling, upcycling, and the use of secondary raw materials.
- Support for local industry and strategic value chains to strengthen European competitiveness and reduce import dependency.
- Harmonised Monitoring, KPIs, and enforcement to ensure measurable progress and consistent implementation across Member States.

Overall, this assessment confirms the technical, economic, environmental, and social superiority of the NEXUS Optimised technology, validating its readiness for industrial scale-up. It also provides actionable insights for policymakers, helping shape the strategic development of sustainable photovoltaic manufacturing in Europe.

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1.1. Description of the deliverable content and purpose

This deliverable provides a comprehensive sustainability evaluation of the NEXUS technologies using an integrated Multi-Criteria Decision Analysis (MCDA) approach. The assessment combines environmental, technical, economic, and social criteria. It is structured into four chapters: **Chapter 2** reviews state-of-the-art sustainability assessment approaches in PV; **Chapter 3** presents current MCDA methods; **Chapter 4** introduces the methodology proposed in the NEXUS project; and **Chapter 5** illustrates the application of MCDA for sustainability evaluation in the project. The purpose is to offer a clear framework to support decision-making and promote sustainable development in photovoltaic energy.

1.2. Relation with other activities in the project

This study integrates and combines results from other project tasks to provide a comprehensive sustainability assessment. Specifically, it gathers economic analysis from Task 5.1, environmental analysis from Task 5.2, circularity analysis from Task 5.3, and social analysis from Task 5.4, creating a holistic framework that supports the MCDA-based evaluation within the NEXUS project.

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2. Sustainability Assessment in Photovoltaics

Sustainability has become a key paradigm guiding technological innovation, policy, and industrial practices. It integrates three interdependent dimensions—environmental protection, economic viability, and social well-being—to meet current needs without compromising future generations (Brundtland Commission, 1987). Circularity, emphasizing resource efficiency, material recovery, and waste minimization, is increasingly incorporated into sustainability analyses.

Applied to photovoltaics (PV), sustainability assessment is crucial. While PV supports the transition to a low-carbon energy system, its rapid deployment raises concerns about raw material availability, waste management, and life-cycle impacts. A comprehensive evaluation must therefore consider environmental, circularity, economic, and social aspects.

2.1. Environmental Assessment

Environmental impacts of photovoltaic (PV) systems are most extensively studied through Life Cycle Assessment (LCA, ISO 14040/14044), which evaluates the full life cycle—from raw material extraction, manufacturing, and operation to end-of-life management. LCA identifies environmental "hotspots," meaning the processes or stages that contribute most to the environmental burden of a PV system, providing crucial information for decision-makers to improve sustainability performance.
Key indicators include:

- **GHG emissions (g CO_2-eq/kWh)**: This measures the carbon footprint of PV electricity. The majority of emissions occur during the production phase, particularly in silicon purification, wafer and cell manufacturing. Reducing energy consumption in these stages is essential for lowering the overall environmental impact (Fraunhofer ISE, 2023).
- **Toxicity**: Human toxicity and ecotoxicity are particularly important for thin-film and perovskite PV technologies due to the use of hazardous materials like lead, cadmium, or selenium. Evaluating these impacts helps identify potential risks to human health and ecosystems across the life cycle (Arbabzadeh et al., 2018).
- **Mineral resource scarcity /Abiotic depletion/ Resource use, mineral and metals** This assesses the use and potential scarcity of critical materials such as indium, silver, tellurium, and rare earth elements. High dependency on these materials can create supply risks and affect the long-term sustainability of PV technologies (Frischknecht et al., 2022; Martin et al., 2022; Hackenhauer et al., 2025).

To ensure comparability and transparency, IEA PVPS Task 12 provides harmonized guidelines for LCA of PV electricity. The methodology recommends standardized functional units, consistent system boundaries, and the reporting of essential impact categories such as GHG emissions, toxicity, and critical material use (IEA PVPS, 2016).

2.2. Economic Assessment

Economic sustainability is typically addressed through Life Cycle Costing (LCC), which complements LCA by including costs over the full life cycle, from manufacturing to end-of-life management (Swarr et al., 2011). In energy economics, standard metrics are also applied:

- **Levelized Cost of Electricity (LCOE),** usually expressed in €/MWh, represents the average cost of producing 1 kWh of electricity over the system's lifetime. It varies depending on the location of production, the technology used, and the application context (e.g., residential, utility-scale) (NREL,2025) (Cristea et al.,2025).

- **Cost of Ownership (CoO),** typically expressed in €/Wp, evaluates the total cost of the technology at the factory gate, including manufacturing, operation, maintenance. CoO is thus a metric that assesses the intrinsic economic performance of the technology itself, independent of deployment conditions (Scorrano et al.2020)

2.3. Social Assessment

The social dimension evaluates the broader societal impacts of photovoltaic (PV) deployment, ensuring that technological development benefits all stakeholders and avoids negative consequences. Social Life Cycle Assessment (S-LCA) provides a framework to systematically assess social impacts across the PV value chain, using both qualitative and quantitative indicators. Key stakeholder groups and social aspects include:

- **Workers**: Safety and well-being in the workplace, including the occurrence of fatal accidents and compliance with labour standards. Ensuring safe working conditions in manufacturing, installation, and maintenance is critical for sustainable PV deployment (Bonilla-Alicea & Fu, 2022).
- **Society:** Respect for indigenous rights, community engagement, and social acceptance of PV projects. PV deployment should avoid displacing or harming local populations and ensure that local benefits, such as employment or infrastructure, are fairly distributed (Koffler et al., 2018).
- **Local Community:** Contribution to broader societal well-being, such as expenditure on education**,** promotion of energy access, and reduction of social inequalities. PV projects can indirectly support social development through taxes, local funding, or improved access to clean energy (Uçar et al., 2024).
- **Value Chain Actors**: Responsible business practices, including avoidance of anti-competitive behaviour and ethical sourcing of critical materials. This ensures the PV value chain operates fairly, transparently, and sustainably (Zhou et al., 2022).

S-LCA methodologies recommend considering all four stakeholder groups to capture the full range of social impacts across the life cycle. Indicators include job quality, health and safety metrics, income distribution, local community benefits, supply chain responsibility, and social acceptance of PV technologies. Integrating social assessment with environmental, economic, and circularity indicators ensures that PV deployment supports equitable, inclusive, and socially responsible energy transitions.

To enable informed decision-making within an eco-design framework, it is essential to integrate economic, environmental, and circularity indicators into a unified sustainability metric. Multi-Criteria Decision Analysis (MCDA) offers a structured approach to combine these diverse indicators, allowing stakeholders to systematically evaluate trade-offs and identify optimal solutions. The next section will explore various MCDA methods, critically examining their advantages, limitations, and suitability for incorporating economic, environmental, and circularity dimensions in the sustainability assessment of photovoltaic systems

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3. Overview of MCDA in Sustainability Assessment

Multi-Criteria Decision Analysis (MCDA) offers a systematic framework for evaluating complex problems that involve multiple, often conflicting criteria. In the context of renewable energy and photovoltaic (PV) systems, MCDA is used to compare different technologies, prioritize alternatives, and support decision-making processes that account for environmental, economic, technical, and social considerations (Pohekar & Ramachandran, 2004; Mardani et al., 2015). By structuring the decision problem and quantifying trade-offs among criteria, MCDA helps stakeholders identify options that align with sustainability objectives. A variety of MCDA methods exist, each with distinct characteristics, strengths, and limitations, which must be carefully considered depending on the decision context.

3.1. MCDA methods

3.1.1. Utility-Based Methods

Utility-based approaches, such as the Weighted Sum Method (WSM) and Multi-Attribute Utility Theory (MAUT), assign scores and weights to each criterion to calculate an overall performance index for each alternative. WSM is straightforward and widely used but assumes linear trade-offs and independence among criteria. MAUT allows for non-linear utility functions, capturing more complex stakeholder preferences, but requires detailed input and extensive stakeholder engagement (Hajkowicz & Higgins, 2008; Belton & Stewart, 2002).

3.1.2. Pairwise Comparison Methods

Pairwise comparison methods evaluate alternatives by comparing them two at a time, helping stakeholders structure decisions intuitively. Analytic Hierarchy Process (AHP) is the most widely used, offering a consistency check to ensure logical judgments (Saaty, 1980). Its extension, the Analytic Network Process (ANP), models interdependencies between criteria, providing a more realistic representation of complex systems (Mehmood et al., 2017). Limitations include sensitivity to subjective judgments and rank reversal issues.

3.1.3. Outranking Methods

Outranking methods, such as ELECTRE and PROMETHEE, rank alternatives by comparing them across criteria without aggregating scores into a single index. They are particularly useful when criteria are heterogeneous or when trade-offs are not easily quantified. These methods can handle partial preference, incomparability, and threshold effects, but they require careful definition of concordance and discordance parameters (Roy, 1996; Brans & Mareschal, 2005).

3.1.4. Fuzzy and Hybrid Methods

Fuzzy MCDA approaches incorporate **uncertainty and imprecision** in stakeholder judgments, using fuzzy logic or fuzzy numbers to better reflect real-world vagueness in criteria evaluation. Hybrid methods combine techniques (e.g., AHP + PROMETHEE or MAUT + fuzzy sets) to leverage the strengths of multiple approaches, improving robustness and adaptability in complex sustainability assessments (Mardani et al., 2015).

3.1.5. Multi-Objective Optimization Methods

Some MCDA frameworks integrate **optimization techniques**, aiming to identify a set of Pareto-optimal solutions that balance conflicting objectives. These methods are particularly useful in PV system design, where trade-offs exist between environmental impact, cost, energy yield, and social benefits. Overall, the choice of MCDA method depends on the decision context, data availability, stakeholder preferences, and the complexity of the criteria interactions. Each method offers a unique balance between transparency, computational complexity, stakeholder engagement, and ability to handle interdependencies, which must be considered when applying MCDA to PV sustainability assessment.

3.2. Limitations and Challenges of MCDA Approaches

Despite their usefulness in supporting complex sustainability decisions, MCDA methods share several common limitations. Most approaches rely on stakeholder judgments to assign weights and scores, introducing subjectivity that can significantly influence results (Belton & Stewart, 2002). They also require comprehensive, high-quality data, which may be incomplete or uncertain, particularly for environmental, economic, social, or circularity indicators (Mardani et al., 2015). Many methods, such as utility-based approaches, assume independence among criteria, oversimplifying real-world interdependencies (Hajkowicz & Higgins, 2008). Complex techniques, including ANP, fuzzy, or hybrid methods, can impose a high cognitive burden and reduce transparency (Ishizaka & Labib, 2011). MCDA outcomes are sensitive to model assumptions—such as linear trade-offs, thresholds, or membership functions—potentially causing rank reversals or shifts in preferences. Additionally, some methods face scalability issues when the number of criteria or alternatives grows, and aggregating heterogeneous indicators into a single metric may obscure important trade-offs. Recognizing these weaknesses allows analysts to select appropriate methods, conduct sensitivity analyses, and complement MCDA with expert judgment, ultimately enhancing the reliability and robustness of PV sustainability assessments (Belton & Stewart, 2002; Hajkowicz & Higgins, 2008; Ishizaka & Labib, 2011; Mardani et al., 2015).
This highlights the importance of developing a new methodology that builds on the strengths of existing approaches while addressing their limitations to provide a more effective and adaptable framework for decision-making.

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4. Proposed MCDA approach

The proposed methodology integrates sustainability assessment approaches with Multi-Criteria Decision Analysis (MCDA) techniques to provide a comprehensive framework for evaluating photovoltaic (PV) technologies. It combines quantitative sustainability evaluation with structured decision-making to support informed, balanced choices.

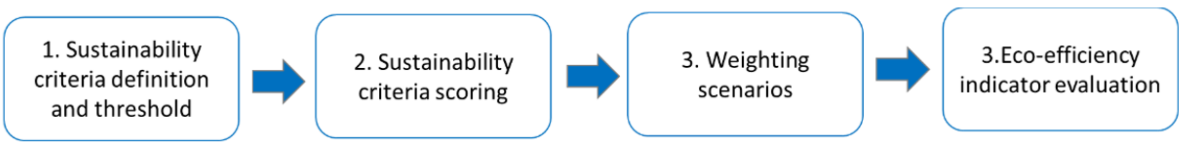
a. Threshold-Based Sustainability Assessment

- Establishes minimum and maximum thresholds for key sustainability indicators, such as GHG emissions, critical material use, recyclability, and social impacts.
- Assesses whether a given technology meets predefined performance criteria, identifying options that satisfy environmental, economic, circularity, and social requirements.

b. Multi-Attribute Utility Theory, MAUT

- Constructs a utility function for each criterion, reflecting its contribution to overall sustainability performance.
- Aggregates the individual utilities using weighted importance factors to calculate a total score for each alternative.
- Allows systematic comparison of technologies by incorporating trade-offs between multiple sustainability dimensions, while enabling stakeholder preferences to be explicitly considered.

By combining threshold-based assessment with MAUT, the methodology leverages the strengths of both approaches: thresholds ensure minimum sustainability compliance, while MAUT provides a nuanced evaluation of trade-offs and overall performance. This integrated framework supports more robust, transparent, and socially responsible decision-making in PV technology selection.



The Figure 1 below details the different steps of the proposed methodology

Figure 1 : Steps of the proposed MCDA methodology

4.1. Sustainability criteria definition and threshold

The criteria were defined based on those most commonly evaluated in the state of the art.
For the environmental assessment, several LCA studies on silicon perovskite (Si/PK) tandem solar cells were considered, focusing only on those applying comparable analytical methods. Based on this, three environmental criteria were selected among those defined in NEXUS milestone 1: carbon footprint, human toxicity, and ressource depletion. Maximum and minimum thresholds were established for carbon footprint and human toxicity according to literature values, while criticality is assessed depending on the type of material chosen.

Regarding the carbon footprint, four recent studies on PV modules were analyzed. (Bartie, 2023) reported a value of 153 kg CO_2-eq/m² with a power density of 273 Wp/m², corresponding to 0.56 kg

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CO_2-eq/Wp. (Roffeis, 2022) found a higher footprint of 217 kg CO_2-eq/m² at 250 Wp/m² (0.87 kg CO_2-eq/Wp). (Lecissici, 2017) reported 163 kg CO_2-eq/m² at 280 Wp/m² (0.58 kg CO_2-eq/Wp), while (Tian, 2020) obtained 223 kg CO_2-eq/m² for 252 Wp/m² (0.89 kg CO_2-eq/Wp). These results highlight the significant influence of module design and material choices on the overall environmental impact, with carbon intensity per unit power ranging from 0.56 to 0.89 kg CO_2-eq/Wp.

For human toxicity, (Celik et al., 2017) reports 4.47×10^{-6} CTUh/m², while (Hosseinian et al., 2020), focusing on nanomaterial use in perovskite module design, found a much higher burden of 5×10^{-5} CTUh/m² due to solvent and precursor toxicity.

According to LCA assessment, silver (Ag) is identified as the most critical material in terms of resource depletion. **ITO** (indium tin oxide) shows significantly lower impacts, particularly regarding the metal resource depletion indicator, making it a good alternative to Ag. Copper (Cu), however, performs even better than both Ag and ITO, offering the lowest impacts and making it the most sustainable choice as an electrode material. (Wagner et al., 2024) showed that critical raw materials for tandem perovskite solar cells in the future may be indium, cesium, gold, and silver.

For the economic criteria, the evaluation of the Cost of Ownership (CoO) in $/Wp was the most commonly used in the state of the art. Recent cost assessments show significant variations between studies. (Mathews, 2020) reported a cost of 24.45 $/m², while (Sofia, 2020) obtained a slightly higher value of 30.75 c$/m². (Bartie, 2023) reported one of the highest costs with 38.10 c$/m², whereas (Cordel, 2025) found an intermediate value of 34.1 c$/m². These results were converted to c$/Wp using the efficiencies defined in the publications. These results illustrate the strong dependence of CoO on material choices, manufacturing routes, and module design.

For the social assessment, a normalized scale was applied, where 1 represents the maximum score (best social performance) and 0 represents the minimum score (lowest social performance). Based on the analysis of Task 5.4, the social indicators were grouped into the following categories: value chain actors, local community, workers, and society.

These publications serve as state-of-the-art references, with reported minimum and maximum values defining representative ranges for each indicator summarized in the Table 1 below. The detailed review of the state of the art for the different sustainability categories (economic, environmental, social) can be found in the respective deliverables D5.1, D5.3 and D5.4.

Table 1: Sustainability criteria definition and threshold

Criteria	Best	Worst
Carbon Footprint	884 kgCO_2éq/kWp	582 kgCO_2éq/kWp
Human Toxicity	2.33.E-08 CTUe/m²	5.00E-05 CTUe/m²
Criticality	Copper Electrode	Silver Electrode
Efficiency	30.5%	21%
Cost	38.5 $/Wp	20.8 $/Wp
Value chain	1	0
Workers	1	0
Local Community	1	0
Society	1	0

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4.2. Sustainability criteria scoring

The sustainability of the technology is evaluated based on six key criteria: carbon footprint, toxicity, criticality, efficiency, social and cost. For each criterion, a reference maximum and minimum value are defined.

❖ **Scoring rules for carbon footprint, human toxicity, cost and social criterion**:

- If the evaluated value exceeds the maximum, the score attributed to the criterion is zero.
- If the evaluated value falls below the minimum, the score is set equal to the full weight assigned to the criterion.
- If the evaluated value lies between the maximum and minimum, the score is calculated as:

$$C(i) = \mathrm{W(i)}\frac{\mathrm{Max(i)} - V(i)}{\mathrm{Max}\ (i) - Min(i)}$$

Where:

- **C(i)** represents the score for criterion (i).
- **W(i)** is the weight assigned to criterion (i), reflecting its relative importance.
- **V(i)** is the evaluated value for the technology.
- **Max(i)** and **Min(i)** are the threshold values defined in Table 1 for each criterion.
-

❖ **Scoring rules for recyclability and efficiency:**

The same formula is applied;

$$C(i) = \mathrm{W(i)}\frac{\mathrm{Min(i)} - V(i)}{\mathrm{Min}\ (i) - Max(i)}$$

however, if the evaluated value exceeds the maximum, the **full weight** is awarded.
If the evaluated value falls below the minimum, the score is **zero**.

❖ **Scoring rules for criticality:**

The score depends on the material used for metallisation and TCO:

- **Copper + AZO:** full score
- **Ag-Cu + AZO** 75%of the total score
- **Ag + ITO :** zero

❖ **Final Eco-Efficiency Indicator:**

The overall eco-efficiency of the technology is calculated as the sum of **all individual criterion scores**

$$C = \sum_{i=0}^{10} C(i)$$

Sustainability Classification:

- If the eco-efficiency scores I> 50, the technology is classified as **Sustainable**.
- If I<25, it is classified as **non-Sustainable**.

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- If 25 <= I <=50, it is classified as **Mostly Sustainable**.

The weights assigned to each criterion can be adjusted depending on project objectives. A sensitivity analysis may be conducted to assess the influence of different weighting schemes on the overall sustainability score

5. Sustainability of the NEXUS project: MCDA application

5.1. Assumption definition

In this section, we evaluate the sustainability of the baseline and optimized technology defined in the NEXUS project using the multi-criteria decision analysis (MCDA) approach described previously. The evaluation considers 10 criteria**,** including environmental indicators (carbon footprint, toxicity, recyclability, criticality), the economic indicator (CoO), social indicators (value chain actors, local community, workers, and society), and the technical indicator (efficiency). The scoring methodology presented in the previous section is applied to calculate the overall eco-efficiency and sustainability classification of the technology.

The two different configurations are illustrated in Figure 2.
The baseline configuration is based on the one analysed in the LCC analysis in Deliverable 5.1, thanks to data collected by FHNW, and based on the experience of OXPV. The optimized configuration presents the following improvements compared to the baseline:

- Silicon wafer of the bottom cell sourced from NORSUN, Norway - 88% hydro powered[1] electricity - instead of China - 60% fossil fuel based[2] electricity.
- Wafer cleaning with less water and solvents consumption, as suggested by CEA
- Cell interconnection with the Electrically Conductive Adhesive (ECA) technique – representing the most used interconnection technique for SHJ cells in Europe – but with 40% of silver compared to the baseline, as suggested by CEA
- Indium-free transparent conductive oxide (TCO) layer, with aluminium zinc oxide (AZO) instead of the most common indium tin oxide (ITO) layer, as suggested by CEA
- Perovskite layer deposition with a solvent-free evaporated technique, instead of the traditional solvent-based deposition, as suggested by KIT

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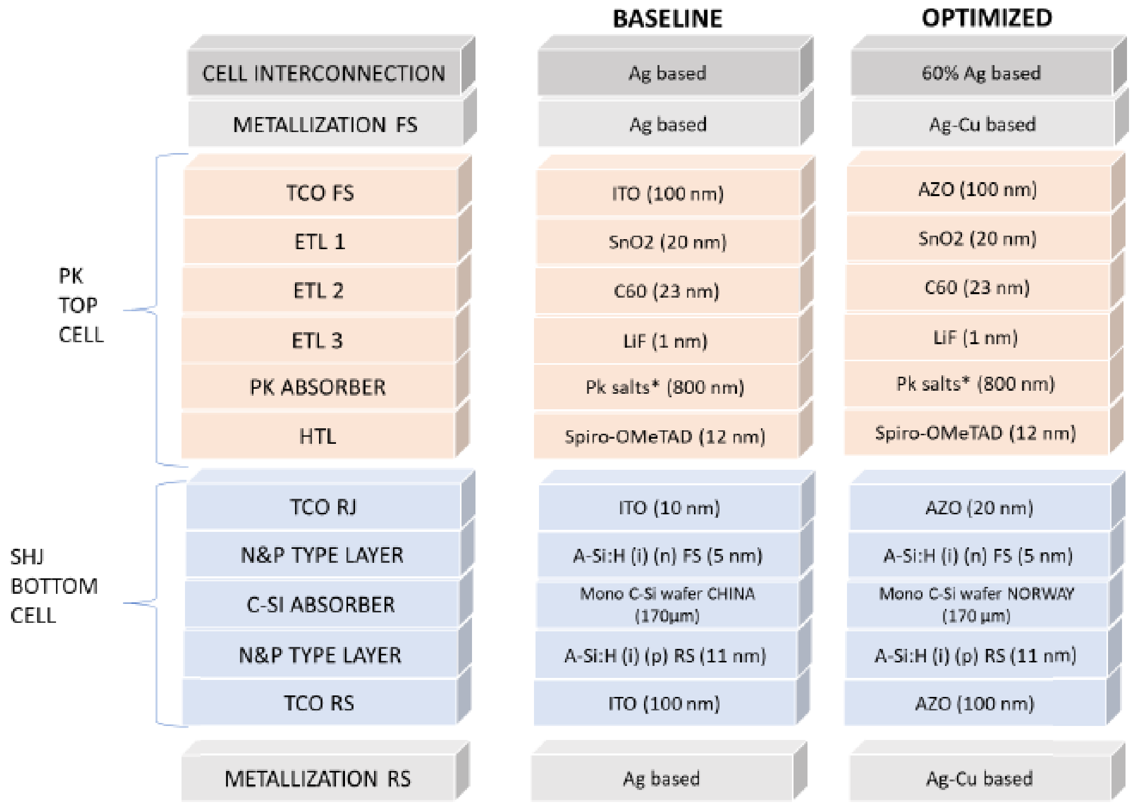

Figure 2 : Simplified representation of the cell architecture in the baseline and optimized configuration (not in scale). *Pk salts: various perovskite salts have been selected based on the experience of OXPV.

Based on the detailed economic, environmental, and social results presented in Deliverables D5.1, D5.3, D5.4, and D5.5, the outcomes for each criterion are summarized in Table 2. The eco-efficiency indicator will then be calculated for both the baseline and the optimized NEXUS technology.

Table 2: Results of the baseline and optimised technology for each criterion

Criteria	Baseline	Optimized Nexus technology
Carbon Footprint	516.88 kgCO2éq/kWp	220.58 kgCO2éq/kWp
Human Toxicity	3.97 E-07 CTUe/m²	3.10 E-07 CTUe/m²
Criticality	Silver Electrode	Silver Copper Electrode
Recyclability	99%	99%
Efficiency	26%	30%
Cost	39.8 $/Wp	34.5 $/Wp
Value chain	0.35	0.28
Workers	0.5	0.31
Local Community	0.9	0.75
Society	0.47	0.23

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5.2. Weighting scenarios for MCDA evaluation

To evaluate the sustainability of the baseline and optimized NEXUS technology, five weighting scenarios were considered using the MCDA approach (Table 3). In scenario 1**,** equal weight is assigned to all categories environmental, technical, social, and economic providing a balanced assessment across all dimensions. Scenario 2 emphasizes environmental criteria, prioritizing reductions in carbon footprint, toxicity, recyclability, and criticality. In scenario 3, technical performance is given priority, focusing on maximizing efficiency, while scenario 4 highlights economic aspects, stressing cost-effectiveness. Finally, scenario 5 prioritizes social criteria, considering the impacts on value chain actors, local community, workers, and society. These scenarios enable an exploration of how different priorities influence the overall eco-efficiency and sustainability classification of the technologies.

Table 3: Weighting scenario per criteria

Criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Environmental criteria	25	70	10	10	10
Technical criteria	25	10	70	10	10
Economic criteria	25	10	10	70	10
Social criteria	25	10	10	10	70

5.3. Results and Interpretation

The results of the eco-efficiency assessment for both the baseline and optimized NEXUS technology under the five weighting scenarios are presented in Table 4. For the baseline technology, the eco-efficiency scores range from 17 to 60. Scenario 4, which prioritizes cost, yields a score of 17, indicating that the technology is **non-sustainable** under this weighting. Scenarios 1, 3, and 5 produce scores between 42 and 48, placing the baseline in the **mostly sustainable** category, while Scenario 2, with environmental criteria prioritized, achieves a score of 60, indicating sustainability. For the optimized Nexus technology, the scores are significantly higher, ranging from 23 to 86. Scenario 4 (cost priority) shows the performance at 41, which is **mostly sustainable showing the improvement of the sustainability of the NEXUIS technology even with high priority of the cost,** NEXUS technology could be sustainable with the adjustment of the attributed weight to the cost. Scenarios 1, 2, 3, and 5 achieve scores between 64 and 86, indicating that the optimized technology is **sustainable** across these scenarios.

Table 4: Results of the MCDA analysis per scenario

Criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Baseline technology	42 Mostly sustainable	56 Sustainable	48 Mostly Sustainable	16 Non-Sustainable	56 Mostly Sustainable
Optimized technology	69 Sustainable	88 Sustainable	84 Sustainable	41 Mostly Sustainable	64 Sustainable

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Overall, the results demonstrate that the optimized NEXUS technology consistently outperforms the baseline, particularly when environmental, technical, or social criteria are prioritized, highlighting the positive impact of optimization on overall sustainability. These results indicate that the technology's sustainability is robust, yet its relative performance is influenced by the strategic priorities considered in the evaluation.

5.4. Guidelines for EU policy levers for future scale-up and deployment of sustainable PV technologies

Following the MCDA, several strategic options for enhancing sustainability and competitiveness in the European photovoltaic (PV) sector were assessed. The analysis identifies four priority axes, each supported by quantitative findings from WP5 and accompanied by actionable recommendations for both EU-level and national policymakers.

Mandatory Eco-Design and LCA Transparency

The MCDA confirms that binding eco-design requirements and systematic LCA disclosure deliver the strongest overall gains in environmental and social performance. To operationalize this:

- **Introduce EU-wide eco-design criteria** requiring reduced silver consumption (e.g., >40% reduction) and the adoption of Ag-Cu pastes, which significantly lower environmental impacts compared to traditional metallization.
- **Mandate environmental performance thresholds** based on proven emission reductions, such as the *50% GHG reduction* achievable when sourcing wafers from low-carbon electricity regions like Norway instead of China.
- **Establish a minimum set of LCA indicators** (GWP, mineral resource use, social risk exposure), including the explicit assessment of critical raw materials such as indium—identified as a bottleneck and strategically motivating **indium-free tandem PV R&D**

Circular Economy Incentive

The MCDA shows that circularity-focused incentives score highly on environmental impact and innovation potential. Recommended measures include:

- **Manufacturer-funded take-back schemes** and/or a **pre-financed recycling fund** to ensure end-of-life recovery, supported by penalties or sales bans for modules not meeting recyclability requirements.
- **Targeted subsidies or VAT reductions** restricted to PV systems meeting circularity and eco-design criteria (e.g., panels incorporating recycled aluminum, which reduces climate impact by ~40%)
- **Bonus scoring in public tenders** for modules produced within EU or resilient value chains, incentivising recycled content, transparent LCA, and design for disassembly
- **Import tariffs or corrective measures** for modules lacking recycling pathways or undercutting the EU market with non-compliant environmental standards.

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Support for Local Industry and Resilient Value Chains

Strengthening European industrial sovereignty is essential, and the MCDA indicates strong benefits across competitiveness, innovation, and social impact. Actionable measures include:

- **Support for regional PV industrial clusters**, facilitating wafer and cell production shifts from high-risk areas to Europe; WP5 results show that relocating wafer production from China to Norway substantially reduces social risks.
- **Strategic funding for EU-based manufacturing of critical components**, prioritising low-carbon electricity regions and circular-material supply chains.
  – **Incentives for local recycling and upcycling infrastructures**, particularly for aluminum frames, glass, and polymer recovery, reinforcing European autonomy in material flows.

Monitoring, KPIs, and Enforcement

The impact of these measures depends on consistent implementation. MCDA findings underline the necessity of enforceability and transparent monitoring. Recommended actions include:

- **Defining measurable KPIs**, such as minimum recycling rates, maximum GWP thresholds per module, or certified shares of secondary materials.
- **Establishing an EU-level monitoring authority** for PV sustainability compliance, with periodic audits and publicly accessible performance dashboards.
- **Strict enforcement mechanisms**, including penalties for non-compliance and progressive tightening of criteria in line with technological improvements identified in WP5.

Together, these four strategic axes—supported by MCDA evidence and reinforced by quantitative WP5 findings—outline a coherent pathway to a sustainable, circular, and competitive European PV sector. They simultaneously improve environmental performance, drive innovation, and strengthen European industrial sovereignty.

6. Summary and Outlook

The present study demonstrates that the baseline and optimized technologies developed within the NEXUS project exhibit a high level of sustainability. A comprehensive review of the state-of-the-art enabled the identification of key sustainability criteria—including carbon footprint, human toxicity,

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recyclability, criticality, and cost—and confirmed the relevance of Multi-Criteria Decision Analysis (MCDA) as an effective framework for integrating multiple criteria into a robust assessment.

Applying the tailored MCDA methodology, with indicators benchmarked against literature values, allowed the evaluation of the baseline and optimized technologies at both laboratory and industrial scales. Eco-efficiency indicators and sustainability classifications, along with sensitivity analyses exploring different criteria weightings, show that the optimized technology consistently outperforms the baseline, particularly when environmental, technical, or social criteria are prioritized. Industrial-scale applications generally exhibit higher eco-efficiency, while sustainability outcomes vary according to the priorities assigned: equal weighting or environmentally- technical, social focused scenarios achieve the highest scores, whereas emphasizing economic aspects reduces eco-efficiency.

Overall, the findings confirm that the technologies' sustainability is robust and provide a clear basis for guiding future technology development and policy measures. To maximize environmental and industrial benefits, it is recommended to integrate sustainability considerations from the design phase, promote circular economy practices such as recycling and use of secondary materials, support regional industrial value chains, and implement measurable performance monitoring. By following these strategic directions, Europe can strengthen the competitiveness of its photovoltaic sector while advancing toward a more circular and sustainable energy transition.

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