

Research Paper

Eco-design suggestions for innovative, lab-scaled perovskite solar cells

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ABSTRACT

The continuous growth of solar photovoltaics demands the introduction of innovative technologies with low carbon footprint, raw material consumption and environmental impacts. In this context, the eco-design of solar photovoltaics is essential to minimize their life cycle environmental impacts while maintaining the ideal usage of the technologies. The study applies life cycle assessment to suggest the eco-design of innovative, lab-scaled perovskite solar cells, with a scenario analysis on their lifetime and conversion efficiency. The assessment indicates that the climate change impact ranges from 0.58 to 6.18 kg CO₂ eq, the fossil resource use is from 7.38 to 7.92 MJ, and the mineral and metal resource use is 1.53 g Sb eq per kWh. The eco-design of perovskite solar cells should focus on materials for electrode, while the scenario analysis points out that its efficiency should reach 25%, with the lifetime of 15 years for competing with the silicon-based counterparts.

1. Introduction

In the last decade, the global installed capacity of solar photovoltaics (PV) grew ten times, reaching 1.87 TW by the end of 2024, with the addition of 453 GW compared to the previous year (IRENA, 2025a). Under the International Renewable Energy Agency (IRENA) scenario of limiting the global warming at 1.5 °C, it is expected that 77% of electricity, being equal to 11.17 TW, would be sourced from renewable energy by 2030, in which a half of the renewable energy capacity would be fulfilled by solar PV, at around 5.46 TW (IRENA, 2024). The similar number is also suggested in the Net Zero Emission scenario of the International Energy Agency (IEA) (IEA, 2025). The leading role of solar PV in ensuring the energy security while meeting the climate targets is expected to be continue by 2050, accounting for about 45% of the total electricity generation by 2050, at 35.7 thousand TWh of electricity (IEA, 2025).

With the increased share and installation capacity of solar energy technologies, it is forecasted that more innovative solar PV technologies will be researched, developed and exploited. These innovative solar PV technologies such as perovskite solar cells (PSCs) offers a great potential for increasing their power conversion efficiency (Cellura et al., 2024). The efficiency of PSCs which started at less than 10% 15 years ago

(Khatoon et al., 2023), now reach 27% (NREL, 2025). A recent research proposed a PSC with double absorber layers, which even achieved an efficiency of more than 31% (Bhattarai et al., 2023). Besides, PSCs allow flexible applications in buildings (Rossi et al., 2024) and greenhouses (Spampinato et al., 2025), thanks to their semi-transparency, permitting light penetration into the buildings and reducing shadow areas on agricultural soil.

In line with the increased exploitation of innovative solar technologies, more resources will be required. On one hand, the demand on resources may cause potential risks of material shortage for manufacturing these technologies themselves (Montana et al., 2024). On the other hand, there is a concern on natural resources for manufacturing the components and infrastructure that support the development and deployment of these technologies and their supply chain (Riva Sanseverino and Luu, 2022). For PSCs, the environmental concerns mostly focus on the potential risk of lead contamination in cases of the cells' break down (Dissanayake et al., 2023), which may occur during natural disasters or incidents, or through the damage on the encapsulant and outer cover, or even in case of uncontrolled end-of-life management of the decommissioned cells.

Although the efficiencies of the PSCs are validated in the laboratory that they outperform the conventional solar PV, the commercial gap still exists. The new challenges, which often go in line with the innovative

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Nomenclatures			
a-Si:H	Hydrogenated amorphous silicon.	LS	Low scenario.
AP	Acidification potential.	LU	Land use.
AS	Average scenario.	MABr	Methylammonium Bromide.
Au	Gold.	MAPbI ₃	Methylammonium Lead Halide.
BS	Base scenario.	MgF ₂	Magnesium Fluoride.
CsFAMA	Cesium Formamidinium Methylammonium.	MJ	Mega Joules.
CsI	Cesium Iodide.	MoO ₃	Molybdenum Trioxide.
DE	Diethyl Ether.	N ₂	Nitrogen.
DMF	Dimethyl Formamide.	NEST	Network 4 Energy Sustainable Transition.
DMSO	Dimethyl Sulfoxide.	ODP	Ozone depletion potential.
EP	Eutrophication potential.	OS	Optimized scenario.
EP-fw	Eutrophication potential, freshwater.	OSC	Organic solar cells.
EP-m	Eutrophication potential, marine.	PbBr ₂	Lead Bromide.
EP-t	Eutrophication potential, terrestrial.	PCOF	Photochemical ozone formation.
ET	Ecotoxicity.	PEF	Product Environmental Footprint.
ET-fw	Ecotoxicity, freshwater.	PEFCR	Product Environmental Footprint Category Rules.
ETL	Electron transport layer.	PMF	Particulate matter formation.
FAI	Formamidinium Iodide.	PSC	Perovskite solar cells.
FTO	Fluorine Tin Oxide.	PV	Photovoltaics.
GWP	Global warming potential.	RI	Respiratory inorganics.
HS	High scenario.	RU	Resource use.
HT	Human toxicity.	Ru	Ruthenium.
HT-c	Human toxicity, cancer.	RU-f	Resource use, fossils.
HT-nc	Human toxicity, non-cancer.	RU-m	Resource use, metals and minerals.
HTL	Hole transport layer.	RuCl ₃	Ruthenium (III) Chloride.
IEA	International Energy Agency.	sc-SSC	Single crystalline silicon solar cells.
IR	Ionizing radiation.	SnCl ₄	Tin (IV) Chloride.
ITO	Indium Tin Oxide.	SnO ₂	Tin (IV) Oxide.
kg CO ₂ eq	kilogram carbon dioxide equivalent.	SSC	Silicon solar cells.
kg Sb eq	kg antimony equivalent.	TiO ₂	Titani (IV) Oxide.
kWh	kilo Watt hour.	TTIP	Titanium Isopropoxide.
LCA	Life cycle assessment.	TW	Tera Watts.
		WU	Water use.

solar cells, such as high costs, limited scalability, and complex fabrication, frequently lack of attention in the literature (Biçer and Krebs, 2025). The number of studies on the costs of PSCs and levelized cost of electricity (LCOE) generated by the cells are limited (Liu et al., 2025). In order to improve the technology readiness level of PSCs, it is essential to conduct an economic analysis since the early design phase of PSCs, to grab any opportunities on cost improvement as soon as possible. In this context, the research and development of lab-scaled PSCs are required to cover not only their efficiency (technical aspects), but also the environmental aspects such as raw material consumption and ecotoxicity and human toxicity, and economic feasibility such as manufacturing cost of the cells and LCOE.

Eco-design integrates the environmental aspect into the product development process, considering its whole life cycle (UNEP, 2021); therefore, it is a suitable approach for innovative solar PV technology development. For the eco-design of the solar PV technologies, life cycle assessment (LCA) and other life cycle thinking-based approaches are commonly applied (Rossi et al., 2016). They are good tools and methods for eco-assessment which quantify and assess the potential environmental impacts, covering from the material extraction to the end of life of the technologies. The obtained results on eco-assessment of solar PV technologies from LCA may be utilized for the eco-improvement of the technologies or the eco-design. The eco-improvement actions can be proposed by identifying the environmental hotspots during the technologies' life cycle, so that some eco-design measures can be implemented regarding these hotspots; conducting several scenario analyses to compare difference factors that affect the environmental profiles of the technologies so that they can be optimized technically and

environmentally. LCA is applicable for environmental aspects, while other life cycle thinking-based approaches such as life cycle costing (LCC) could be integrated to extend the traditional coverage of eco-design to include the economic aspects.

There are many LCA case studies on solar PV technologies for the technologies' eco-assessment. A quick search on 'sciencedirect.com' with terms 'life cycle assessment' and 'solar PV' results more than 18 thousand publications. However, for LCA of PSCs, the number of publications is limited in 14 papers until 2025. These LCA studies quantified the life cycle environmental impacts of the cells, and some cases compared several PSC types, or PSCs with other solar PV cells such as silicon-based, cadmium telluride thin films, dye sensitized, or organic cells. For the eco-improvement purposes of PSCs, e.g. identify environmental hotspots and conducting scenario analysis for proposing eco-design actions, there are only three papers available (Akulenko et al., 2023; Luu et al., 2026; Zhang et al., 2017a). Interestingly, one of these papers proposed eco-design measures for PSCs without conducting an LCA. Instead, the authors only focused on the end-of-life stage by evaluating the recyclability of PSCs based on life cycling thinking concepts, e.g. circular economy (Akulenko et al., 2023).

In term of economic aspects, the studies are limited in 9 papers, which calculated the manufacturing costs and (or) LCOE generated from PSCs. The manufacturing costs of PSCs ranges from very low, at 2.7 US dollars per m² of active layer for 100 MW production scale (Çulfk et al., 2022), or average, at 34–140 US dollars per m² of module, at large scaled production for various recipe of PSCs' layers (Ahangharnejhad et al., 2022; Chang et al., 2017; Li and Chen, 2024), to very high, at 8.16–32.9 Eur per cm² at lab-scaled PSCs (Luu et al., 2026).

Table 1 summarizes the main points of LCAs, economic analysis and eco-design of PSC in the literature.

Among these LCA and economic analysis studies, most of the paper consider the environmental and economic aspects separately. There are only three papers simultaneously quantifying both life cycle environmental impacts of PSCs and their life cycle costs, or their manufacturing costs, or their LCOEs. Besides, the eco-design measures are withdrawn from the LCA results, rather than a combination of technical considerations, quantification of life cycle environmental impacts and economic analysis.

This study applies LCA and LCC on PSCs to quantify their life cycle environmental impacts, identify any environmental hotspots during their life cycle, assess their economic feasibility and suggest several eco-design measures. The studied PSCs are innovative products, being developed in the laboratory, therefore, this study has dual aims of providing LCA results of innovative PSCs (eco-assessment) and contributing to the eco-design of solar PV technologies (eco-improvement). Moreover, the eco-design of PSCs in this paper does not limit in environmental aspects (as it is traditionally defined) but also cover the economic aspect of the PSCs.

2. Data and method

The study adheres to the recognized LCA standards (ISO 14040 and ISO 14044), following the four steps of goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. This section provides the general information about the studied PSCs, the goal and scope of the LCA study (method), and life cycle inventory (data) used in the study. The life cycle impacts assessment and interpretation (hotspot, sensitivity analysis, scenario analysis) will be presented in the next section (Results and Discussion).

2.1. Goal and scope definition

The paper quantifies the life cycle environmental impacts and costs of the innovative, lab-scaled PSCs. The obtained LCA and LCC results will be applied for the further development of PSCs with considerations of their environmental impacts and economic feasibility, and eco-design of the technologies. All the life cycle environmental impacts will be quantified per one kWh of electricity (functional unit) as recommended by IEA (Frischknecht et al., 2016) and the Product Environmental Footprint Category Rules (PEFCR) (EC, 2021).

This study concerns four PSCs being researched and developed under the “Network 4 Energy Sustainable Transition” (NEST) Spoke 1 project, with various materials for electron transport layers, absorbers and hole transport layers. Three of these studied PSCs (ENEA24, ENEA25, and ENEA26) are added with an interlayer made of MgF_2 to improve the efficiency of the cells, while one remaining PSC (UNIPA27) is made with common materials and structure of PSCs, without any interlayer. The studied product systems are similar to those being reported in (Luu et al., 2026). Description of the cells' layers are summarized in Table 2, and Fig. 1 illustrates the studied products.

The system boundary of ‘cradle to gate’ will be applied for LCA, covering from resource extraction, cell fabrication, panel production, system installation and electricity generation. Meanwhile the system boundary of ‘gate to gate’ will be applied for LCC, meaning that only costs for fabricating the PSCs are quantified and assessed. The system boundaries of the study are presented in Fig. 2. The environmental impacts from end-of-life stage, being related to cells' disassembly and disposal, are inconsiderable compared to the life cycle impacts (Alberola-Borràs et al., 2018b; Zhang et al., 2017b), therefore they are excluded in this study. For LCC, costs of upstream processes such as research and development, and downstream processes such as use and disposal of PSCs are excluded due to lack of information. Besides, costs for infrastructure, e.g. laboratory equipment are excluded as the equipment are used for several research funds and activities, which are

impossible for allocated the costs for the research and development activities of the studied PSCs only. Environmental and social externalities are also excluded due to their complexity.

Regarding the life cycle impact assessment method, the selected methods are Product Environmental Footprint (PEF) (Damiani et al., 2022) for environmental impacts and life cycle costs with a quantification of LCOE. The same equations as (Luu et al., 2026) are applied in this study to quantify the life cycle impacts and costs.

2.2. Life cycle inventory

The data for foreground processes of fabricating the PSC are on-site data, which was provided by the NEST project' partners from their laboratories. Some on-site data, which was unavailable, was taken from literature. Specifically, the amount of molybdenum trioxide used for hole transport layer is taken from (Ancil et al., 2020). The amount of nitrogen and electricity is quantified based on the actual duration working with various equipment and the specific power consumption in (Alberola-Borràs et al., 2018a), and nitrogen consumption in (Sánchez et al., 2019). Data for the background processes was taken and adapted from Ecoinvent database (Ecoinvent, 2020). Data on the production of specific chemicals and materials, which was used for fabricating the solar cells, was modelled based on the stoichiometric approach. The main inputs and outputs for fabricating the PSCs are mentioned in Table 3.

Except for UNIPA27, the three remaining PSCs compose of six layers, following six main processing steps. First, the indium tin oxide (ITO) coated glass is prepared by cleaning with acetone and ethanol. In the second step, the MgF_2 interlayer of 1 nm thickness is deposited by spin coating and heating. The third step concerns the deposition of the electron transport layer (ETL). A 50 nm thickness ETL is deposited by spin coating at 6000 rpm for 30 s and annealing (starting at 100 °C, reaching 150 °C in 10 mins, and the total annealing time is 3600 s). Next, the perovskite absorber layer is deposited on ETL layer in a two-step spin coating process. The precursor solvent is freshly prepared by mixing the materials (methylammonium iodide MAI, lead iodide PbI_2 , lead bromide PbBr_2 , formamidinium iodide FAI, methylammonium bromide MABr) with anhydrous N,N dimethylformamide:dimethyl sulfoxide (DMF:DMSO), at different ratios depending on the specific PSCs. The solution is spin coated at 1000 rpm for 10 s in the first step spin coating, then annealing at 50 °C for 120 s. The second step spin coating is at 5000 rpm for 45 s, then annealing at 100 °C in 600 s. The fifth step involves the deposition of the hole transport layer (HTL) by thermal evaporation of MoO_3 or spin coating of SpiroOMETAD. The last step is the gold deposition, being done by thermal evaporation on top of the HTL layer.

There are several assumptions regarding the transportation of materials and electricity consumption for the cells' fabrication. The distance of transporting the materials for fabricating the solar cells is assumed to be from the suppliers in Rome to the laboratories of the NEST Spoke 1 project' partners in Rome (20 km) and Palermo (924 km). The vehicle is assumed to be lorry > 32 t, EURO 4 emission standard, as recommended in IEA's guidelines and PEF (EC, 2021; Frischknecht et al., 2016). Moreover, it is assumed that the production and installation occur in Italy, i.e. the Italian grid mix will be applied for the use of electricity during these stages. Assumptions and inventory data on transportation and electricity mix can be seen in Table 4.

2.3. Scenario development

Several scenarios have been developed with different assumptions on lifetime and power conversion efficiency of the innovative cells, to identify the required technical features of the innovative cells to enter the market. Five scenarios include base scenario (BS) with the multi crystalline silicon cell's efficiency (18%) and its average lifetime (30 years), low scenario (LS) with low efficiency (22%) and short life time

Table 1
LCA, LCC and eco-design of PSC.

Study	Product	Environment impacts	Economic analysis	Functional unit	System boundary	LCA/ LCC results	Eco-design measures
(Celik et al., 2016)	Several PSCs structures and two manufacturing methods	Yes	No	1 kWh of electricity	Cradle to gate	Environmental impacts of PSCs are higher than conventional silicon-based cells per functional unit, due to the low lifetime PSC without hole transport layer has the lowest environmental impacts among the studied PSCs	N/A
(Cai et al., 2017)	Two PSCs	No	Yes	kWh	Gate to gate	LCOEs are from 3.5 to 4.9 US cents per kWh	N/A
(Chang et al., 2017)	PSCs with three large scale production techniques	No	Yes	1 m ² of perovskite module	Gate to gate	The manufacturing costs of perovskite modules range from 87 to 140 US dollars per m ²	N/A
(Zhang et al., 2017a)	Five PSCs	Yes	No	1 cm ² of active area	Cradle to gate and cradle to grave	Methylammonium lead iodide and Formamidinium lead iodide PSCs have higher environmental impacts than other studied PSCs due to the quantity of organic solvents used for manufacturing the cells. Gold electrode accounts for the highest share of environmental impacts of PSCs. End-of-life treatment with energy recovery is better than landfill	Replacement of gold with silver or aluminium can significantly reduce the environmental impacts
(Alberola-Borràs et al., 2018b)	Four PSCs and three manufacturing methods	Yes	No	1 cm ² of active area	Cradle to grave	Contribution of lead to the environmental impacts is inconsiderable. Reuse and recycling are favourable end-of-life management strategies, significantly reducing resource use and toxicity impacts, compared to landfilling	N/A
(Alberola-Borràs et al., 2018a)	PSCs with carbon stacked electrode	Yes	No	1 kWh of electricity	Cradle to gate	Perovskite layer accounts for the largest impacts among all layers due to energy consumption in preparing and annealing the precursor solution	N/A
(Sánchez et al., 2019)	PSCs with two manufacturing methods	Yes	No	1 kWh of electricity	Cradle to gate	Flash infrared annealing method is 8% of environmental impacts, and 2% of fabrication cost lower than antisolvent method	N/A
(Hosseiniian Ahangharnejhad et al., 2020)	Bifacial perovskite modules	Yes	No	1 m ² of perovskite module and 1 kWh of electricity	Cradle to end-of-use	Bifacial PSCs show an average 17% increase in energy yield compared with mono-facial PSCs. GWPs of the cells range from 11 to 15 g CO ₂ eq per kWh	N/A
(Ramamurthy Rao et al., 2021)	PSCs with titanium dioxide nano-rod electron transport layer	Yes	No	1kWh	Cradle to grave	GWPs is at 182 g CO ₂ eq per kWh. Balance of the system and assembly stage accounts for more than 56% of total GWP.	N/A
(Hadi and Heidari, 2021)	PSCs	Yes	Yes	1 m ² of perovskite façade	Cradle to gate	Perovskite module has lower environmental impacts than cadmium telluride and dye sensitized modules. Perovskite has the highest life cycle costs at 547 US dollars and its levelized cost of electricity is 0.15 US dollars per kWh.	N/A
(Kajal et al., 2022)	Carbon based PSCs	No	Yes	1 W and 1 kWh of electricity	Gate to gate	Manufacturing cost is 0.15–0.21 US dollars per W and LCOE is from 1.47 to 3.4 US cents per kWh, depending on	

(continued on next page)

Table 1 (continued)

Study	Product	Environment impacts	Economic analysis	Functional unit	System boundary	LCA/ LCC results	Eco-design measures
(Correa Guerrero et al., 2021a)	PSCs	Yes	No	1 m ² of PSC	Gate to gate	specific modules and assumed lifetime. Total energy requirement for the whole system is 259.6 kWh, in which 98% is used for the process	N/A
(Ahangharnejhad et al., 2022)	PSCs	Yes	No	1 m ² of PSC	Gate to gate	The manufacturing cost of perovskite module is 34 US dollars per m ²	N/A
(Li et al., 2022a)	PSCs with graphene electrode	Yes	No	1 m ² of PSC	Cradle to gate	Graphene electrode contributes the largest share to the total impacts	N/A
(Okoroafor et al., 2022)	PSCs with two manufacturing methods	Yes	No	1 kWh of electricity	Cradle to gate	Electricity consumption contributed the highest share to the majorities of the impacts.	N/A
(Čulík et al., 2022)	PSCs in different locations	No	Yes	m ² of perovskite module and 1 kWh of electricity	Gate to gate	The manufacturing cost ranges from 2.7 to 8.1 US dollars per m ² of active layer for 100 MW production scale, depending on types of PSCs LCOE range from 3.6 to 5.9 US cents per kWh of electricity depending on locations	N/A
(Akulenko et al., 2023)	PSCs	Yes	No	N/A	End of life	N/A	Eco-design should focus on materials and cells' structure to allow the easy separation and recovery of critical materials
(Rossi et al., 2024)	Perovskite modules in buildings	Yes	Yes	1 kWh of electricity from roof perovskite module and 1 m ² vertical façade with perovskite module	Cradle to use	Compared to glass, perovskite modules are preferred for façade applications. However, for roof installation, silicon solar PV modules are preferred.	N/A
(Li and Chen, 2024)	PSCs with metal and carbon electrode	No	Yes	1 m ² of perovskite module	Gate to gate	Manufacturing cost of carbon perovskite module is 41.16 US dollars per m ² , which is half of the manufacturing cost of the modules with metal electrode	N/A
(Zhao et al., 2024)	PSCs and two manufacturing methods	Yes	Yes	1 m ² of perovskite module	Cradle to use	Gold electrode contributes the largest share to the total impacts for both manufacturing method Manufacturing cost for 1 m ² of perovskite module ranges from 101 Eur to 13,881 Eur depending on scale of production (pilot vs laboratory) and electrode materials (carbon vs gold) GWP of perovskite module with carbon electrode at pilot scale is 12 g CO ₂ eq per kWh	N/A
(Luu et al., 2026)	PSCs with interlayer	Yes	Yes	1 kWh of electricity	Cradle to grave	GWPs of PSCs range from 0.12 to 0.15 kg CO ₂ eq per kWh, depending on choice of materials. The total cost ranges from 8.16 to 32.9 Eur per cm ²	Improving efficiency and lifetime of the cells; Changing materials and fabrication processes; Reducing the environmental impacts of electron transport layer, absorber and electrode

Table notes: AP: Acidification potential, CED: Cumulative energy demand, EP: Eutrophication potential, ET: Ecotoxicity, GWP: Global warming potential, HT: Human toxicity, IR: Ionizing radiation, LU: Land use, ODP: Ozone depletion potential, PCOF: Photochemical ozone formation, PMF: Particulate matter formation, PSC: Perovskite solar cell, RI: Respiratory inorganics, RU: Resource use, RU-f: Resource use, fossils, RU-m: Resource use, metals and minerals, WU: Water use.

(10 year), average scenario (AS) with average efficiency and life time (25% and 15 years) and high scenario (HS) with high efficiency (26%) and relatively long lifetime (17 years) and optimized scenario (OS) with very high efficiency (28%) and long life time (20 years).

In the base scenario, the efficiency and lifetime of PSCs are assumed to be similar to those commercial solar cells, which are used in the LCA conducted by IEA for several types of solar PV systems (IEA, 2024). This

scenario supports the quantitative comparison of life cycle impacts of PSCs and commercial silicon-based solar cells. The remaining scenarios indicate the expected progress of PSC research and development. The efficiency of PSCs rosed from 14.1% befor 2015 to around 25.5% in 2020 (NREL, 2025). In the LS and AS, the efficiencies of PSCs are set around these numbers to indicate the increasing progress. Recently, the studies by University of Science and Technology of China in 2024 and

Table 2

Description of perovskite solar cells.

Solar cell	Substrate	Interlayer	Electron transport layer	Absorber	Hole transport layer	Electrode
ENEA24	Glass with ITO	MgF ₂	SnO ₂	MAPbI ₃	a-Si:H	Au
ENEA25	Glass with ITO	MgF ₂	Ru doped SnO ₂	MAPbI ₃	MoO ₃	Au
ENEA26	Glass with ITO	MgF ₂	SnO ₂	CsFAMA	MoO ₃	Au
UNIPA27	FTO coated glass	None	TiO ₂	MAPbI ₃	SpiroOMETAD	Au

Table notes: ITO: Indium Tin Oxide, MgF₂: Magnesium Fluoride, SnO₂: Tin (IV) Oxide, MAPbI₃: Methylammonium Lead Halide, a-Si:H: hydrogenated amorphous silicon, Au: Gold, Ru: Ruthenium, MoO₃: Molybdenum trioxide, CsFAMA: Cesium formamidinium methylammonium, FTO: Fluorine Tin Oxide, TiO₂: Titani(IV) Oxide.

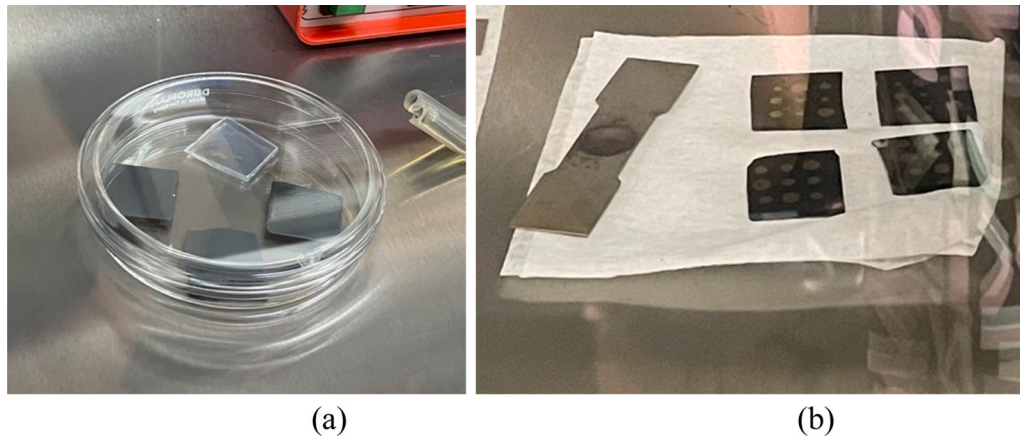


Fig. 1. The studied PSC cells (a) Cells in the chamber after 10 days and (b) Cells in the chamber, full of nitrogen for inert and dust free environment.

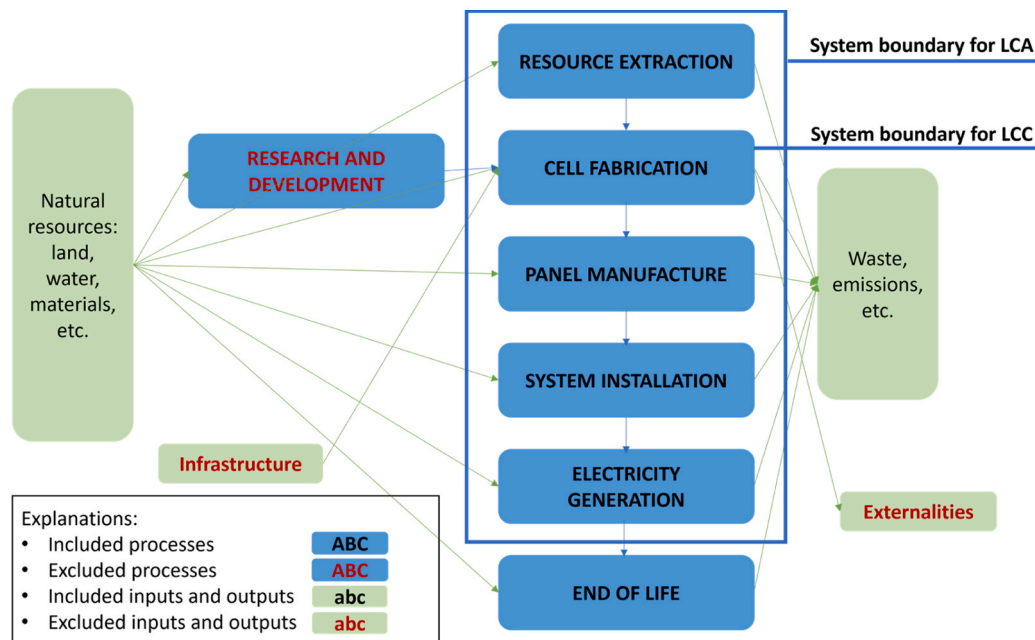


Fig. 2. System boundaries of the study.

Soochow University /UNSW in 2025 reported the higher efficiencies at 26.7% and 26.9%, respectively (NREL, 2025). Therefore, the HS indicate an efficiency which is the closest to actual technology advance, while the OS indicated the best scenario of future advancement in PSC research and development.

The lifetimes of the cells in LS, AS, HS and OS are set to increase from 10 years to 20 years. For the conservative purpose, some previous LCA studies assumed a lifetime of 2 years for PSCs (Gong et al., 2015; Li et al., 2022b). The recent studies reported a lot of progress in improving the PSCs' stability (Islam et al., 2026), which rises to 2000 h (Gao et al.,

2024), 3000 h (Li et al., 2025) and even 4000 h (Liu et al., 2023). In line with the increase in the stability, the operational hours and lifetime of the cells will certainly be increased. Guerrero et al. studied the life cycle environmental impacts and energy related indicators of PSCs and found out that the lifetime of PSC should be above 4.2 years to obtain an energy return of investment (EROI) to be viable for commercialization (e.g. EROI above 3) (Correa Guerrero et al., 2021b). The review of He et al. (He et al., 2020) set up a lifetime of 10 years for PSC, which is considered as the time for the technology maturation, and reported that some of the papers (being reviewed) realized a lifetime of 10 years until

Table 3Main inputs and outputs for fabricating 1 cm² of the perovskite solar cells.

Input/ Output	Unit	PV cells				Ref
		ENEA24	ENEA25	ENEA26	UNIPA27	
ITO (FTO) glass	cm ²	6.25E + 00	6.25E + 00	6.25E + 00	6.25E + 00	
MgF ₂	g	4.05E−06	4.05E−06	4.05E−06		
SnO ₂	g	1.98E−04		1.98E−04		
SnCl ₄	g		3.04E−06			
RuCl ₃	g		3.48E−07			
TTIP	g				3.50E−02	
Isopropanol	g				3.93E−01	
MAPbI ₃	g	1.93E−03	1.93E−03		1.27E−01	On-site data provided by the NEST project's partners
PbBr ₂	g			8.97E−08		
FAI	g			2.01E−07		
MABr	g			2.49E−08		
CsI	g			4.33E−07		
DMF	g	1.89E−03	1.89E−03	8.39E−04	1.89E−01	
DMSO	g	2.45E−04	2.45E−04	1.47E−03		
DE	g	1.57E−03	1.57E−03			
Chlorobenzene	g			2.55E−03	2.21E−01	
a-Si:H	cm ²	1.00E + 00				
SpiroOMeTAD	g				1.45E−02	
Au	g	1.52E−02	1.52E−02	1.52E−02	1.52E−02	
MoO ₃	g		1.56E−05	1.56E−05		(Ancitil et al., 2020)
N ₂	kg	2.57E−01	2.57E−01	2.57E−01	2.57E−01	(Sánchez et al., 2019)

Table notes: ITO: Indium Tin Oxide, FTO: Fluorine Tin Oxide, MgF₂: Magnesium Fluoride, SnO₂: Tin (IV) Oxide, SnCl₄: Tin (IV) Chloride, RuCl₃: Ruthenium (III) Chloride, TTIP: Titanium Isopropoxide, MAPbI₃: Methylammonium Lead Halide, PbBr₂: Lead Bromide, FAI: Formamidinium Iodide, MABr: Methylammonium Bromide, CsI: Cesium Iodide, DMF: Dimethyl Formamide, DMSO: Dimethyl Sulfoxide, DE: Diethyl Ether, a-Si:H: Hydrogenated amorphous silicon, MoO₃: Molybdenum Trioxide, Au: Gold, N₂: Nitrogen.

Table 4

Assumptions on transportation and electricity mix.

Ecoinvent dataset	Unit	PV cells			
		ENEA24	ENEA25	ENEA26	UNIPA27
Transportation, freight, lorry > 32 metric ton, EURO4 {RER}	tkm	5.24E−03	5.24E−03	5.24E−03	2.44E−01
Electricity, low voltage {IT}	MJ	3.37E−01	3.46E−01	5.32E−01	1.62E−01

Table notes: RER: Rest of European countries (excluding Switzerland), tkm: ton kilometer, IT: Italian.

reaching the threshold of 80% of the initial efficiency, with the degradation rate of 2% per year. The lifetime of PSC is expected to be better year by years, consequently, the lifetime of PSC in this study is set at 10 years at minimum, and increasing accordingly in the optimized scenario.

Apart from efficiency and lifetime of the PSCs, the solar radiations are different among the cells and scenarios, causing various amount of electricity being generated over the life cycle of the cells. In the BS, the average solar radiation of Europe is applied for all four PSCs, with the similar efficiency and lifetime of conventional SSC. In the remaining

scenarios (LS, AS, HS and OS), the actual solar radiations of Rome and Palermo, where the cells are studied, are applied. In LS scenario, the efficiency increases but the lifetime decreases compared to BS, representing the slow improvement in technological development. The HS is the most practical scenario in term of the efficiency, while the LS is the most feasible for expected lifetime. The efficiency and lifetime of PSCs gradually increase from LS to OS, causing an increase in electricity generation over these four scenarios. Five scenarios are developed and presented in Table 5.

3. Results and discussion

This section reports the life cycle environmental impacts of the studied PSCs. The environmental hotspots during the cells' life cycle are identified to suggest the components or layers of the cells on which the eco-design measures should be focused. A sensitivity analysis is conducted on the environmental hotspot to indicate the reductions in their life cycle environmental impacts in case the eco-design measures are implemented on those components and/ or layers. Besides, the scenario analysis compares the life cycle environmental impacts of cells with various assumptions on efficiency and lifetime, so that the ideal technical features of the cells could be proposed, supporting the upgrade in the technology readiness level (TRL) of the PSCs. The economic analysis

Table 5

Electricity generation over the cells' lifetime by scenarios.

Scenario	Solar radiation [kWh/m ² /yr]		Efficiency [%]	Lifetime [year]	Electricity generation over lifetime [kWh for 1 m ² of cell]			
	ENEA cells	UNIPA cell			ENEA24	ENEA25	ENEA26	UNIPA27
BS	1331		18%	30	5.03E + 03	5.03E + 03	5.03E + 03	5.03E + 03
LS	1683	1729	22%	10	2.96E + 03	2.96E + 03	2.96E + 03	3.04E + 03
AS	1683	1729	25%	15	5.05E + 03	5.05E + 03	5.05E + 03	5.19E + 03
HS	1683	1729	26%	17	5.59E + 03	5.59E + 03	5.59E + 03	6.11E + 03
OS	1683	1729	28%	20	7.54E + 03	7.54E + 03	7.54E + 03	7.75E + 03

Table notes: BS: Base scenario, LS: Low scenario, AS: Average scenario, HS: High scenario, OS: Optimized scenario. All cells are assumed to be installed in Europe, with the average solar radiation of Europe in base scenario. ENEA cells include ENEA24, ENEA25 and ENEA26, being installed in Rome and UNIPA cell is UNIPA27, being installed in Palermo, for four remaining scenarios. Data on solar radiation is taken from (ENEA, 2023).

is conducted for the same purpose of supporting the cells' TRL improvement, which points out the cost for fabricating the PSCs and LCOE generated by these cells.

3.1. Life cycle environmental impacts

The life cycle environmental impacts were calculated by using SimaPro software (PRé Sustainability, 2021) and applying PEF as life cycle impact assessment methods (EC, 2021). The life cycle assessment indicates that the global warming potential (GWP) of PSC ranges from $5.83\text{E}-01$ – $6.18\text{E}-01$ kg CO₂ eq per kWh. The resource use, fossils (RU-f) is from $7.38\text{E}+00$ – $7.92\text{E}+00$ MJ, and the mineral and metal resource use (RU-m) is $1.54\text{E}-03$ kg Sb eq per kWh. Other life cycle environmental impacts of PSCs from cradle to gate, per kWh of electricity are presented in Table 6. UNIPA27 has the highest impacts for more than half of the impact categories, including freshwater ecotoxicity (ET-fw), particulate matter (PMF), eutrophication (EP), human toxicity, cancer (HT-c), land use (LU), photochemical ozone formation (PCOF), RU-m and water use (WU). While ENEA26 has the highest impacts for acidification (AP), GWP, non-cancer human toxicity (HT-nc), and RU-f. ENEA25 is the cell with the best eco-profile, with the lowest environmental impact for most of the impact categories, except for ionising radiation (IR). The difference among these cells is insignificant for most of impact categories, except for IR and water use (WU). Notably, the EP-fw and RU-m are the same for four cells, although the cells' layers are different from each other, except for the electrode layer. This may be explained by the considerable contribution of electrode layer to these impacts compared to those of other layers. The contribution of electrode layers to various will be verified in the next section on environmental hotspot identification.

The life cycle environmental impacts of PSCs in this study are in the ranges of similar products in the literature. Specifically, the GWPs of PSCs in the literature are from $3.01\text{E}-02$ – 9.50 kg CO₂ eq per kWh (Alberola-Borràs et al., 2018a; Ramamurthy Rao et al., 2021; Sánchez et al., 2019; Zhang et al., 2017a). The range is quite large due to the methodological choice and assumptions of the case studies, for examples the system boundary of the study, scale of production, manufacturing processes, end-of-life treatment strategies, and lifetime of the cells. The higher end of PSC was 6.78 kg CO₂ eq per kWh, being reported by (Okoroafor et al., 2022), who quantified the cradle to grave environmental impacts per kWh with the assumption of one year lifetime. In other case, Alberola-Borràs et al. reported the cradle to gate GHG

emissions of PSC which were at 9.50 kg CO₂ eq per kWh for lab-scaled production, and $3.01\text{E}-02$ kg CO₂ eq per kWh for industrial production (Alberola-Borràs et al., 2018a). In term of resource use, the RU-m of PSCs in the literature is from $3.39\text{E}-07$ – $9.33\text{E}-04$ kg Sb eq per kWh (Alberola-Borràs et al., 2018a; Okoroafor et al., 2022). Again, this large range is caused by the methodological choice and assumption of the case studies. The higher end of this range is RU-m for kWh of electricity generated by lab-scaled PSC, at $9.33\text{E}-04$ kg Sb eq, which is slightly lower than the RU-m of PSCs in this study, at $1.54\text{E}-03$ kg Sb eq per kWh.

Compared to the commercial SSCs, the life cycle environmental impacts of PSCs in the NEST project are considerably higher. For an example, the GWP of the NEST project's PSC is 1.4 times higher than that of single crystalline SSC (sc-SSC), at $4.29\text{E}-02$ kg CO₂ eq (IEA, 2024). Similarly, the RU-f of PSCs in this study is 1.5 times higher than that of commercial sc-SSC. Notably, the RU-m of PSCs in this study triples that of sc-SSC. It should be noted that the sc-SSCs which was assessed by IEA, has the same efficiency and lifetime in BS (being referred in the Section 2.3. Scenario development).

In other recent case studies, the reported GWPs of PSCs are higher than those of SSCs. For an example, the review of (Müller et al., 2021) reported that GWPs of SSC were between $1.29\text{E}-02$ – $2.99\text{E}-02$ kg CO₂ eq for glass - glass and glass - backsheets panels produced in EU, Germany and China. The GWPs of PV installed in Malaysia were within this range, at $2.86\text{E}-02$ – $2.91\text{E}-02$ kg CO₂ eq per kWh (Tan et al., 2026). Meanwhile, the study of (Khan et al., 2024) highlighted a larger variation, with the lowest value at $1.59\text{E}-02$ kg CO₂ eq for SSC manufactured with Norway grid and the highest value at $4.04\text{E}-02$ kg CO₂ eq for SSC manufactured with Chinese grid. In all these cases, the GWPs of PSCs being studied in this paper are much higher than the numbers reported in the most updated literature for commercial SSCs globally.

Considering that the PSCs can be applied in buildings, their GWP can be compared to those of SSCs installed in buildings such as rooftop and façade systems. In these cases, the GWPs of SSC-based rooftop system was at $3.6\text{E}-02$ kg CO₂ eq, and those of façade systems were from $5.14\text{E}-02$ – $2.14\text{E}-01$ kg CO₂ eq depending on the cardinal direction facing (Virtuani et al., 2023). In such case the GWPs of the studied PSCs are higher than those of SSCs being applied in buildings with similar installation location, e.g. European.

The large difference between the environmental impacts of innovative PSCs in this study and PSCs and commercial SSCs indicates that there is a gap between laboratory scale and industrial scale. This gap

Table 6
Life cycle environmental impacts per kWh of electricity generated by PSCs.

Impact	Unit	Value					
		ENEA24	ENEA25	ENEA26	UNIPA27	Lab-scaled PSC	IEA's commercial sc-SSC
AP	mol H + eq	$8.50\text{E}-03$	$8.46\text{E}-03$	$8.61\text{E}-03$	$8.54\text{E}-03$		$3.60\text{E}-04$
GWP	kg CO ₂ eq	$5.91\text{E}-01$	$5.83\text{E}-01$	$6.18\text{E}-01$	$6.00\text{E}-01$	$9.50\text{E}+00$	$4.29\text{E}-02$
ET-fw	CTUe	$1.97\text{E}+02$	$1.97\text{E}+02$	$1.97\text{E}+02$	$1.98\text{E}+02$	$2.87\text{E}+02$	
PMF	disease inc.	$9.66\text{E}-08$	$9.61\text{E}-08$	$9.68\text{E}-08$	$1.00\text{E}-07$		$3.85\text{E}-09$
EP-m	kg N eq	$2.92\text{E}-03$	$2.91\text{E}-03$	$2.93\text{E}-03$	$2.96\text{E}-03$		
EP-fw	kg P eq	$1.12\text{E}-02$	$1.12\text{E}-02$	$1.12\text{E}-02$	$1.12\text{E}-02$		
EP-t	mol N eq	$3.60\text{E}-02$	$3.60\text{E}-02$	$3.62\text{E}-02$	$3.65\text{E}-02$		
HT-c	CTUh	$4.88\text{E}-09$	$4.88\text{E}-09$	$4.89\text{E}-09$	$4.90\text{E}-09$	$1.04\text{E}-06$	
HT-nc	CTUh	$5.34\text{E}-07$	$5.34\text{E}-07$	$5.35\text{E}-07$	$5.34\text{E}-07$	$1.24\text{E}-05$	
IR	kBq U-235 eq	$2.75\text{E}-02$	$2.68\text{E}-02$	$3.13\text{E}-02$	$2.40\text{E}-02$		
LU	Pt	$8.95\text{E}+00$	$8.93\text{E}+00$	$9.10\text{E}+00$	$9.46\text{E}+00$		
ODP	kg CFC11 eq	$2.04\text{E}-08$	$2.03\text{E}-08$	$2.12\text{E}-08$	$2.13\text{E}-08$		
PCOF	kg NMVOC eq	$7.96\text{E}-03$	$7.94\text{E}-03$	$8.05\text{E}-03$	$8.14\text{E}-03$		
RU-f	MJ	$7.48\text{E}+00$	$7.38\text{E}+00$	$7.92\text{E}+00$	$7.67\text{E}+00$		$5.10\text{E}-01$
RU-m	kg Sb eq	$1.54\text{E}-03$	$1.54\text{E}-03$	$1.54\text{E}-03$	$1.54\text{E}-03$	$9.33\text{E}-04$	$5.21\text{E}-06$
WU	m ³ depriv.	$7.26\text{E}-01$	$7.21\text{E}-01$	$7.45\text{E}-01$	$8.63\text{E}-01$		$4.49\text{E}-03$

Table notes: AP: Acidification potential, GWP: Global warming potential, ET-fw: Ecotoxicity, freshwater, PMF: Particulate matter formation, EP-m: Eutrophication potential, marine, EP-fw: Eutrophication potential, freshwater, EP-t: Eutrophication potential, terrestrial, HT-c: Human toxicity, cancer, HT-nc: Human toxicity, non-cancer, IR: Ionizing radiation, LU: Land use, ODP: Ozone depletion potential, PCOF: Photochemical ozone formation, RU-f: Resource use, fossils, RU-m: Resource use, minerals and metals, WU: Water use.

could be filled by improving the fabrication process of the cells, in which both electricity and material consumption should be more efficient so that the required energy and resources are reduced and optimised. Table 6 compares the environmental impacts of innovative PSC in this study, lab-scaled PSCs in Alberola et al.'s study (Alberola-Borrás et al., 2018a) and commercial sc-SSC (IEA, 2024).

3.2. Environmental hotspot identification

Regarding the contributions of layers to the life cycle impacts, most of the impacts come from electrode, accounting for more than 90% of the impacts for most of impact categories such as AP, ET-fw, PMF, EP, HT, LU, PCOF, RU-m. It is also the largest contributors for other impact categories, with lower shares, such as GWP (75% to 79%), RU-f (68% to 72%). Besides, glovebox and substrate are environmental hotspots, in which glovebox is the largest contributor for IR (42% to 60%), and second largest contributor for ODP (from 41% to 44%), while most of the water is used for cleaning the substrate. It is suggested that in order to improve the eco-design of PSCs, the environmental impacts from electrode should be reduced. Particularly, a resource-efficient process should be applied for depositing the electrode into the cells. Other materials for electrode could be studied to replace the precious metal, e.g. gold which is currently used in the electrode. Fig. 3 presents the contribution of different layers to the environmental impacts of ENEA24. The contributions of layers to the life cycle impacts of other studied PSCs share the similar patterns as those of ENEA24.

Electrode contributes to approximately 100% of some impacts such as ET-fw, EP-fw, HT-nc, RU-m for all four studied PSCs. Because electrodes of the studied PSCs are the same, the four above mentioned impacts are very similar. Although the cells are made from various combinations of materials for absorber, ETL, HTL and interlayer, the contributions of these layers are so insignificant compared to the electrode that they do not cause any visible difference on the obtained results of ET-fw, EP-fw, HT-nc and RU-m.

3.3. Sensitivity analysis

Due to the significant contribution of electrode to the total impact, the sensitivity analysis is conducted on the amount of gold using for

fabricating the electrode of the innovative PSCs. By applying the best available technique, the amount of gold used for the electrode can be reduced hundred times compared to the actual amount of gold consumption in the NEST's laboratory, from $1.52\text{E}-02$ g to $1.10\text{E}-04$ g (Alberola-Borrás et al., 2018b). Thanks to the reduction in the gold consumption, all the impacts drop, from at least 1 time to 90 times. Notably, the RU-m significantly reduces from $1.54\text{E}-03$ kg Sb eq to $1.62\text{E}-05$ kg Sb eq per kWh, being equal to 94 times drop at average. Besides, some impacts such as ET-fw, EP-fw and HT-nc, also see considerable reductions, at around 60–80 times. Some other impacts such as GWP, IR, ODP, and WU also reduce, but to a lesser extent. For example, GWP reduces 3.6 times at average, from $5.98\text{E}-01$ kg CO₂ eq to $1.63\text{E}-01$ kg CO₂ eq per kWh. Fig. 4 presents the reductions of some impacts in the sensitivity analysis.

3.4. Scenario analysis

This section analyses the role of efficiency and lifetime to the eco-

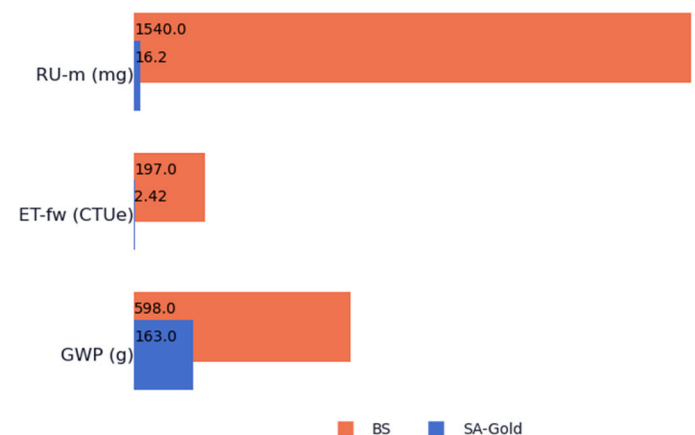


Fig. 4. Reduction of impact in sensitivity analysis. Figure notes: SA-Gold: Sensitivity analysis on gold consumption, GWP: Global warming potential, ET-fw: Ecotoxicity, freshwater, PMF: RU-m: Resource use, minerals and metals, WU: Water use.

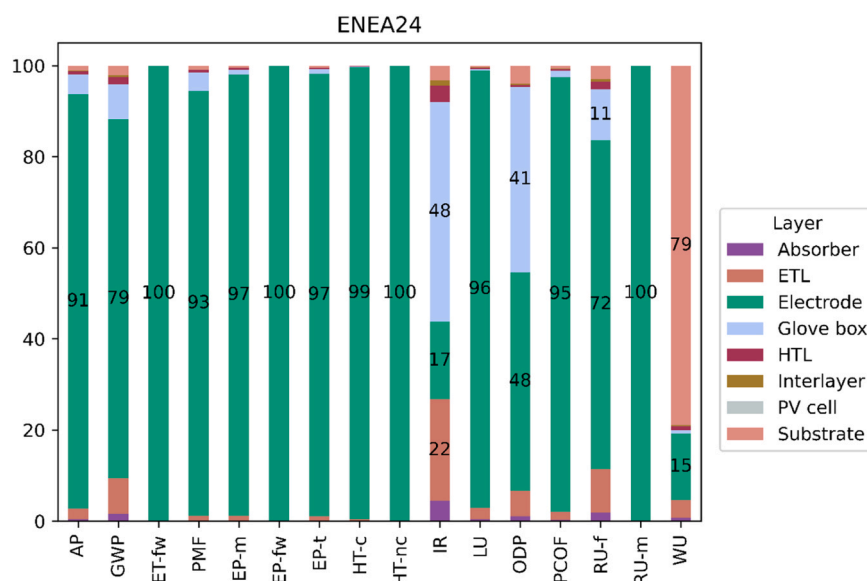


Fig. 3. Share of impact by layers of ENEA24. Figure notes: AP: Acidification potential, GWP: Global warming potential, ET-fw: Ecotoxicity, freshwater, PMF: Particulate matter formation, EP-m: Eutrophication potential, marine, EP-fw: Eutrophication potential, freshwater, EP-t: Eutrophication potential, terrestrial, HT-c: Human toxicity, cancer, HT-nc: Human toxicity, non-cancer, IR: Ionizing radiation, LU: Land use, ODP: Ozone depletion potential, PCOF: Photochemical ozone formation, RU-f: Resource use, fossils, RU-m: Resource use, minerals and metals, WU: Water use.

profile of the cells. The eco-profile of PSCs by scenarios are illustrated in Fig. 4, for (a) GWP, (b) RU-f, (c) RU-m, (d) ET, (e) HT-c, and (f) HT-nc. The life cycle environmental impacts were highest in the LS, with efficient at 22% and 10 years of lifetime. In case the efficiency increases to 25% with 15 years of lifetime in AS which are similar to the technical estimation of the best available PSC being studied in the laboratories [23], [24], the amount of electricity generation of PSC is similar to that of commercial SSCs. Accordingly, the environmental impacts in AS are very similar to those in BS. In HS and OS, the efficiencies as well as lifetime increase, being equal to two thirds of BS. In such case, to improve the eco-profile of the cells, it is important to increase the power

conversion efficiency and lifetime of the cells. By optimizing these technical properties, the environmental impacts of the cells per kWh of electricity are significantly reduced. In order to compete with the commercial SSC, PSCs need to at least fulfil the same energy generation amount over their life cycle, e.g. achieving at least 25% of power conversion efficiency for 15 years of lifetime.

In Fig. 5, the GWP and RU-f of commercial SSCs are illustrated, in order to compare between the impacts of lab-scaled PSCs and commercial SSCs. It should be noted that the impacts of commercial SSCs are much lower than the impacts of lab-scale PSCs in this study, due to the scale of production.

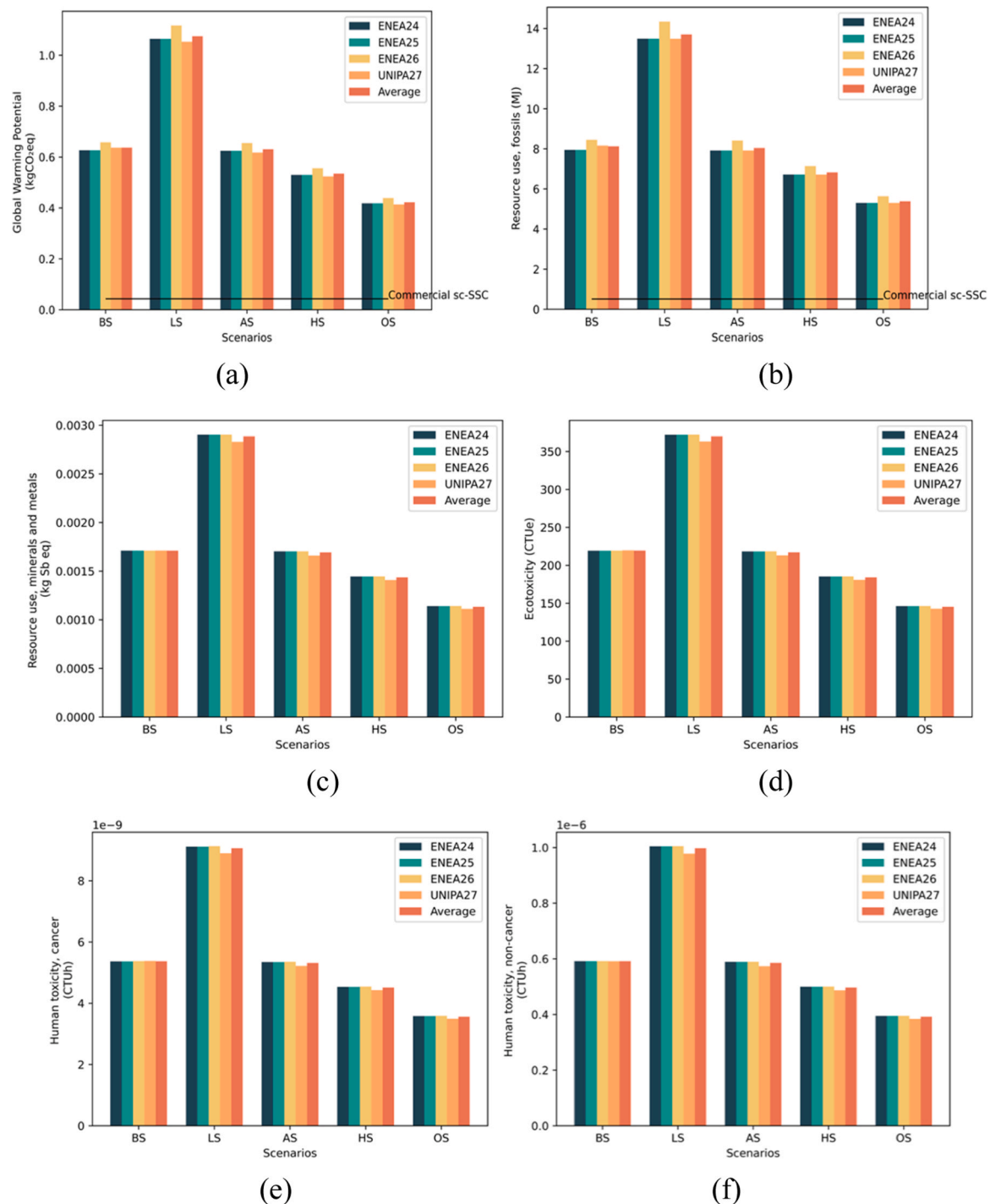


Fig. 5. Scenario analysis for impacts: (a) Global warming potential, (b) Resource use, fossils, (c) Resource use, metals and minerals, (d) Ecotoxicity, (e) Human toxicity, cancer, and (f) Human toxicity, non-cancer.

3.5. Economic analysis

For the upscale of the innovative PSCs, apart from increasing the cells' efficiency and lifetime, it is necessary to optimize the fabrication costs and the LCOE being generated from the cells. The costs of fabricating the PSCs at the laboratory range from 6.02 Eur to 10.09 Eur per cm^2 . There are not many differences among the fabrication cost of ENEA24, ENEA25 and ENEA26, which are innovative cells with the integration of an interlayer, at around 6 Eur per cm^2 . Meanwhile the cost for UNIPA27 which is 1.5 times higher, mostly comes from the higher costs for material. The costs for fabricating the PSCs are presented in Fig. 6.

As it can be seen from Fig. 6(a), the costs for energy and transportation account for such small parts that they are invisible, while 99% of the costs are spent on materials. Because the majority of costs are spent on the purchase of materials, it is suggested to increase the resource efficiency of the manufacturing stages to reduce the costs of these innovative, lab-scaled PSCs. For an example, if the amount of gold used for electrode reduces (as being mentioned in sensitivity analysis), the fabrication costs of PSCs decrease accordingly from 6 Eur to 4 Eur for ENEA cells, and from 10 Eur to 8 Eur for UNIPA cells. It should be noted that the amount of electricity for depositing the electrode and the material transportation reduce slightly in line with the reduction of material consumption. However, it is not indicated in the calculation due to small shares of energy and transportation in the total cost.

In case the fabrication costs of PSCs are converted into LCOEs, the costs range from 7.6 to 17.9 Eur per kWh of electricity generated by the studied PSCs (Fig. 6(b)). The LCOEs have the same patterns with the fabrication cost, in which LCOE generated by ENEA PSCs are similar at 10.8 Eur per kWh, and reduce to 7.7 Eur per kWh in case of reduction in gold consumption for electrode (sensitivity analysis). The LCOEs of UNIPA27 are higher, at 14.9 and 17.9 Eur per kWh for the sensitivity analysis and the initial calculations. Being compared to the LCOE of commercial solar PV globally, at 4.3 US cents per kWh, or those of solar PV in Europe, from 4.1 to 10.3 US cents per kWh in 2024 (IRENA, 2025b), the LCOEs of these lab-scaled PSCs are significantly higher. These differences likely originate from the production scale, e.g. lab-scaled fabrication, which is costly to buy materials at small quantity, and low resource and energy efficiency for fabrication processes, for example spin coating of cells' layers at laboratory scale vs. slot-die coating in pilot scale or inkjet and screen printing at industrial scale.

3.6. Scalability from laboratory to industry

The mass production of PSCs requires the change in materials and

fabrication processes. Conventionally, PSC's electrode is made of gold or silver which are efficient conductors. However, they are costly and unstable due to the chemical corrosion caused by the migration of halide ions from perovskite layer to the electrode, resulting in the formation of gold or silver iodide (Astakala et al., 2026). There are several materials being proposed for PSC's electrode to replace gold or silver such as carbon-stack, graphene and dielectric-metal-dielectric (DMD). Carbon is an abundant material which is a promising solution to balance the cost, stability and performance of PSC (Farokhi et al., 2025). Study on environmental impacts of carbon-based PSC indicated the potential for pre-industrial and industrial production of PSCs thanks to the improvements in the environmental impacts for most of the layers in carbon stack PSC (Alberola-Borrás et al., 2018a). Graphene (Li et al., 2022b) and DMD (Giuliano et al., 2019) are also attractive materials for transparent or semi-transparent electrode for building applications, while delivering high performance.

In term of fabrication processes, the traditional fabrication process such as spin coating will be replaced by new techniques which allow the mass production such as roll-to-roll (R2R), blade coating and slot die coating. R2R process enables the continuous manufacturing of flexible PSC, which are suitable for wearables and building applications. R2R feeds a long roll of flexible substrate through printing, coating, drying and encapsulation steps without stopping, consequently reducing cost and increasing efficiency printing (Astakala et al., 2026; Priya and Stonier, 2025). Blade coating and slot die coating are methods for depositing the perovskite layer. In blade coating, a blade is used to disperse the perovskite precursor on substrate on a hot platform. As the precursor solution evaporates, the thin film will be formed on the substrate. This method has the advantages of low cost, fast processing and high productivity, therefore, being suitable for industrial production. By better selection of additive, solvent engineering and defect passivation, the quality of perovskite films and performance of PSC will be improved (Xiao et al., 2021). Blade coating has been reported to apply in sheet-to-sheet process, while slot die coating has been used in R2R process. In slot die coating, a nozzle with a narrow slit is used to dispense the precursor solution on the substrate. The nozzle is very close to substrate and the slit is narrow; therefore, the wastage level is minimized. Slot die coating was applied to deposit the perovskite layer of stack device, resulting in device with high efficiency on both flexible glass and plastic substrate (Patidar et al., 2020). Despite of new materials and techniques being introduced, challenges remain in terms of the cells' stability, film uniformity and defect management for mass production and commercialization of PSCs.

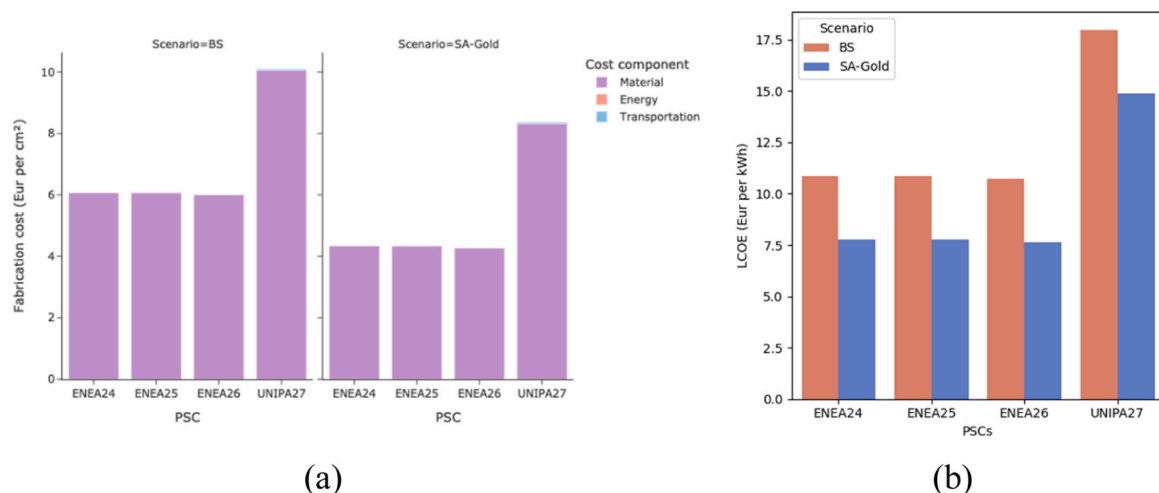


Fig. 6. Fabrication cost and LCOE of PSCs.

4. Conclusion

The paper quantifies the life cycle environmental impact of one kWh of electricity generated by innovative PSCs from cradle to gate and compares it with that of PSCs in the literature. The LCA results indicates that the climate change impacts of PSC ranges from $5.85\text{E}-01$ – $6.20\text{E}+00$ kg CO₂ eq per kWh. The RU ranges from $7.39\text{E}+00$ – $7.93\text{E}+00$ MJ for fossils, and at $1.54\text{E}-03$ kg Sb eq per kWh for metals and minerals. These results are very similar to life cycle environmental impacts of lab-scaled PSCs in the literature, being lower in terms of GWP, ET and HT, slightly higher for RU-m. However, the life cycle environmental impacts of PSCs are significantly higher than those of commercial SSCs. The comparisons with other PV cells suggested that there is an opportunity for the lab-scale PSCs in this study to improve their technical performance and reducing their life cycle environmental impacts, in order to aim at the upscale of these innovative solar PV cells. In this case, the improvements can be made in term of selecting a more environmental-friendly material, increasing the energy and resource efficiency of the fabrication processes.

It is identified that electrode layer is the major contributor for most of the impacts; therefore, further study should focus on this layer. In case the resource efficiency increases in term of gold consumption for the electrode, the environmental impacts will considerably reduce from 1 to 3 times in IR, WU and GWP to 80–90 times in ET-fw, EP-fw and RU-m. Besides, the materials for electrode layer should be carefully selected, with the consideration of energy consumption for preparing the materials and fabricating the layer. Other materials which are less precious and more abundant (than gold) are encouraged. Innovative structures should be studied, for an example: adding dielectric layers to create a transparent DMD electrode. This will not only reduce the environmental footprint of the PSCs but also extend the application of PSCs for purposes requiring various light transmittance while maintaining high energy conversion efficiency, for examples building integrated PV windows, and agrivoltaics in green houses.

The scenario analysis points out the importance of improving the technical properties of the cells in reducing their environmental impacts. By increasing the power conversion efficiency and extending the cells' lifetime, the environmental impacts of the cell (per kWh of electricity generated) will reduce. In case the efficiency of PSCs reaches 25%, with the lifetime of 15 years, the amount of electricity generation and relevant environmental impacts of PSCs over their life cycle become similar to those of commercial SSC, and suitable for large scale production.

The economic analysis indicates high fabrication costs for lab-scaled PSCs, and correspondingly high LCOEs, ranging from 7.6 to 17.9 Eur per kWh. Most of the costs come from the purchase of materials, while the costs for energy consumption during the fabrication processes and transportation of materials accounts for small share of the total. Compared to the commercial solar PV, the fabrication costs and LCOEs of the studied PSCs are much higher, which are due to the lab-scale fabrication of PSCs. It is suggested that the future research should cover the up-scaled production to better understand the environmental impacts and costs of these innovative PSCs.

It is concluded that first, electrode material substitution is identified as the highest-priority intervention. The hotspot analysis consistently identifies the electrode layer as the dominant environmental contributor across most impact categories. Replacing gold with carbon-based alternatives or DMD structures reduces freshwater ecotoxicity and eutrophication by 80–90 times, and lowers GWP, ionising radiation and water use by a factor of 1–3. This result is robust across all four studied cells and constitutes a concrete, actionable target for any future PSC architecture.

Second, the simultaneous improvement of power conversion efficiency and cell lifetime should be pursued as a coupled technical objective. The scenario analysis demonstrates that reaching 25% efficiency with a minimum 15-year lifetime substantially reduces per-kWh environmental impacts, narrowing the gap with commercial silicon PV.

Development strategies should therefore integrate both dimensions within a unified optimisation framework.

Third, material cost optimisation is essential to approach commercial competitiveness. LCOE values range from 7.6 to 17.9 EUR per kWh – one to two orders of magnitude above commercial PV benchmarks. Since material procurement dominates fabrication costs, strategies combining material recovery, reduced consumption per unit area, and adoption of earth-abundant alternatives simultaneously serve both environmental and economic objectives.

The eco-design, therefore, should at least compose of these following actions:

- Focusing on innovative materials and structures of electrode layer such as carbon and DMD.
- Combining efforts of materials, cells' structure and fabrication processes for improving the efficiency and lifetime of the cells (technical aspects) to minimize environmental impacts per kWh of electricity generated.
- Optimizing the cost of materials to reduce the cost of cells and LCOE.

CRediT authorship contribution statement

Le Quyen Luu: Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Sonia Longo:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Roberta Rincione:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Maurizio Cellura:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Francesco Guarino:** Writing – review & editing, Writing – original draft, Investigation, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Le Quyen Luu, Maurizio Cellura and Francesco Guarino reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data is provided in the article.

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