Energy Reports 15 (2026) 108961

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Recommended actions for eco-design of solar energy technologies based on life cycle approach

Le Quyen Luu, Maurizio Cellura *, Francesco Guarino, Sonia Longo

University of Palermo, Palermo, PA, Italy

ARTICLE INFO

Keywords:
Solar PV
Concentrating solar power
Eco-design
Life cycle assessment
Life cycle costing
Guidelines
Sustainable energy transition

ABSTRACT

Innovative solar energy technologies bring the benefit on the global decarbonization; nevertheless, they require certain raw materials and cause several environmental impacts. These impacts can be minimized through the application of eco-design measures. The paper applies life cycle assessment and life cycle costing on innovative solar photovoltaics cells and concentrating solar power technologies, from which eco-design measures are identified to improve the technologies technically, environmentally, and economically. For solar photovoltaics, materials for electrode and absorber layer are the most influencing factors to the eco-profile of the cells; therefore, the selection of materials, and the optimization of the fabrication process for depositing these layers would further reduce the cells' life cycle environmental impacts. By selecting different combinations of materials, the global warming potential of lab-scaled perovskite solar cells may be as low as 0.12–0.15 kg CO_2 eq per kWh, and mineral and metal resource use could be reduced to the value between 1.54E-05 and 1.61E-05 kg Sb eq. For concentrating solar power, the eco-design should focus on minimizing the use of the natural gas in co-generation components, and improving the eco-profiles of collector, heat transfer fluids and power generation unit among solar-to-power components. Other life cycle stages such as transportation, consumption and end-of-life, though contribute small shares of the total impact, need to be taken into account for the best and combined effect of the eco-design measures. These measures reduce not only the environmental impacts but also the electricity cost, to bring the innovative solar energy technologies closer to the market readiness level.

1. Introduction

Energy sector contributes to three quarters of the global greenhouse gas (GHG) emissions, up to nearly 35 Gt CO_2 eq in 2022 (IEA, 2022a), making the decarbonization of energy sector becomes unavoidable, with the substantial contribution of renewable energy technologies such as solar photovoltaics (PV) and wind energy. Solar PV in particular, is expected to grow up to 8519 GW of installed capacity by 2050, providing 25 % of the total electricity demand (IRENA, 2019) and be the top contributor to the net zero emissions (IEA, 2021). However, solar energy technologies themself, and the power supporting technologies such as electronics and energy storage systems heavily depends on the raw materials, especially critical and strategic raw materials (IEA, 2022b; Montana et al., 2024).

Fortunately, more than 70 % of the environmental impacts such as the carbon footprint, raw material consumption as well as other environmental impacts of these innovative solar energy technologies can be estimated since the designing process (Zhang et al., 2015). Similarly, up to 75 % of the life cycle costs are decided early at the product design stage (Dahmani et al., 2022). These environmental impacts and costs can be minimized through applying the eco-design approach, as a preventative method at the early stage during the design of the technologies in the lab.

In eco-design, the environmental aspects are considered during the product development process. It takes into account environmental impacts throughout the product life cycle, aiming at the lowest possible environmental impacts (UNEP, 2021).Various eco-design methods and tools have been studied in the literature, such as life cycle assessment (LCA) tools, computer aided design integrated tools, diagram tools, checklists and guidelines, design for X approaches, etc. (Rossi et al., 2016). Among these tools, LCA is popular for the eco-design of products, as it quantifies and evaluates all potential environmental inputs and outputs through the entire life cycle of the product or service (ISO, 2006a), which is in line with the concept of eco-design to integrate environmental aspects into the design of the product over all life cycle stages (UNEP, 2021). In fact, there are many LCA case studies on solar energy technologies for their eco-assessment. A quick search on Scopus

* Corresponding author.
E-mail address: maurizio.cellura@unipa.it (M. Cellura).

https://doi.org/10.1016/j.egyr.2025.108961
Received 20 July 2025; Received in revised form 16 October 2025; Accepted 21 December 2025
Available online 13 January 2026

Nomenclatures

BIPV	Building integrated photovoltaics
$Ca(NO_3)_2$	Calcium nitrate
CED	Cumulative energy demand
cm^2	Square centimeter
CsFAMA	Cesium formamidium methylammonium
CSP	Concentrating solar power
CST	Concentrating solar thermal
EP-fw	Eutrophication potential, freshwater
EP-m	Eutrophication potential, marine
EP-t	Eutrophication potential, terrestrial
ET-fw	Ecotoxicity, freshwater
ETL	Electron transport layer
GW	Gigawatt
GWP	Global warming potential
HT-c	Human toxicity, cancer
HT-nc	Human toxicity, non-cancer
HTF	Heat transfer fluid
HTL	Hole transport layer
kg CO_2 eq	Kilogram carbon dioxide equivalent
KNO_3	Potassium nitrate
kWh	Kilowatt hour
LCA	Life cycle assessment
LCC	Life cycle costing
LCOE	Levelized cost of electricity
$MAPbI_2$	Methylammonium lead iodide
MJ	Megajoule
MoO_3	Molydenum trioxide
$NaNO_3$	Sodium nitrate
NEST	Network for Sustainable Energy Transition
ODP	Ozone depletion potential
OSC	Organic solar cell
P3HT	Poly(3-hexylthiophene) polymer
PCBM	Phenyl-C61-butyric acid methyl ester
PEDOT PSS	Poly polystyrene sulfonate polymer
PEF	Product environmental footprint
PET	Polyethylene terephthalate (plastic)
PSC	Perovskite solar cell
PTHS	Parabolic trough hitec salt
PTSS	Parabolic trough solar salt
PV	Photovoltaics
Ru	Ruthenium
RU-f	Resource use, fossils
RU-m	Resource use, metals and minerals
Si	Silicon
SnO_2	Tin (IV) oxide
SSC	Silicon solar cell
STHS	Solar tower hitec salt
STSS	Solar tower solar salt
TES	Thermal energy storage
TiO_2	Titanium dioxide

with terms "life cycle assessment" and "solar energy technologies" results in more than 1200 publications. However, the number of publications reduces to 15 publications, in case the search is narrowed down to "eco-design", e.g. aiming at eco-improvement of the product. The papers with eco-design recommended actions for some specific solar energy technologies are limited in the recent case studies which applied LCA to integrate environmental criteria into the design of perovskite solar cell (PSC) based on TiO_2 nanotube (Zhang et al., 2015), organic solar cells (OSCs) applied as solar rooftop and portable solar charger (Tsang et al., 2016), multijunction silicon solar cells (SSCs) (Blanco et al., 2020), thin film PV cells (Jones et al., 2024), concentrating solar power (CSP) (Dumortier and Haussener, 2015), concentrating solar thermal (CST) (Albertí et al., 2019), and hybrid system of CSP and solar PV (Bahlawan et al., 2019). In term of methodological choice, the selected functional units in the existing case studies are diverse in kWh, cm^2, system, etc, and the system boundaries are various, covering from cradle to gate, cradle to grave or only the end-of-life stage.

Table 1 summarizes the key aspects of applying LCA for the eco-design in the literature.

One common feature of these case studies is that in order to propose eco-design measures, they either conducted comparative LCAs, identified hotspots during the product's life cycle, or developed scenarios of material change, component replacement or waste management strategies. For examples, (Tsang et al., 2016) compared OSC and SSC; (Blanco et al., 2020) compared multi-junction and traditional SSC; and (Albertí et al., 2019) compared solar hot water system with natural gas one. In other case study, (Zhang et al., 2015) identified the environmental hotspots during the life cycle of PSC. Regarding scenario development approach, (Olmedo-Torre et al., 2018) studied various heat transfer fluids (HTFs), e.g. materials used in CSP plants. (Dumortier and Haussener, 2015) developed several scenarios of combining CSP components such as photo absorber, electrode, electrocatalyst. Several recycling technologies of solar PV were studied in (Ratner et al., 2020). Through these quantification and analysis, the most environment-friendly option is identified, from which eco-design suggestions could be formulated.

In most of the cases, LCA is applied as a stand-alone tool to quantify environmental impacts. This is likely due to the fact that eco-design is environmentally oriented. Limited cases cover other aspects of product development such as economic and financial feasibility. Economic aspects were considered for the eco-design of HTF applied in parabolic trough CSP plant in Italy by taking into account of the price of the fluids together with their technical performance and environmental impacts (Olmedo-Torre et al., 2018). In other study, Rossi et al. quantified the life cycle costing (LCC) of solar PV system (Rossi et al., 2020).

In this study, apart from life cycle environmental impacts, the economic aspects of the innovative solar energy technologies will be studied by applying LCC, so that the recommended eco-design actions for the technologies will bring double benefits of environmental and economic sustainability. The cost for fabricating the cells and levelized cost of electricity (LCOE) are quantified and compared with those of the conventional technologies, from which the economic hotspots will be identified and recommended actions for reducing the cost can be proposed, in order to bring the innovative technologies to be close to the market readiness.

Though the existing case studies cover the innovative solar cells such as PSC and OSC, none of them considers the change of materials, for examples materials for various layers of solar cells. In this study, the LCA and LCC are conducted on innovative solar energy technologies, including PSCs, OSC and CSP, which are studied and developed under the Network for Sustainable Energy Transition (NEST) Spoke 1 project. Regarding the PSCs, several choices of materials for electron transport layer, interlayer of the cells will be compared to identify the best combination of materials. The life cycle inventory data is actual data of fabricating the solar PV cells, being taken from the laboratories of the project's partners.

In summary, the contributions of the paper include both the applied method as well as technical results:

- Diversifying the application of LCA: Traditionally, LCA is used for eco-assessment. By quantifying life cycle impacts of solar energy technologies, comparing them with those in the literature and

Table 1
Key aspects of LCA application for the eco-design of solar energy technologies.

Technology	Method and indicator	Functional unit	System boundary	Eco-design suggestions	Paper
PSC based on TiO_2 nanotube	LCA	1 cm^2 active cell	Cradle to gate	Solvent used in perovskite dye synthesis and TiO_2 nanotube is the environmental hotspot, being responsible for more than half of total embodied energy and a third of embodied material consumption. The second hotspot is the energy consumption of the process. It is suggested that the solvent should be reduced or reclaimed, and the manufacturing process should be improved to be more energy efficient.	(Zhang et al., 2015)
OSC applied as solar rooftop and portable solar charger	LCA	two functional units of 1 kWh and 10 Wh of electricity	Cradle to grave	OSCs have the better environmental profile than SSCs for both applications. It is potential to improve the environmental profile of solar energy sector by using OSCs for simple and short-term applications e.g. without ancillary components such as mounting structure for solar rooftop, or case for solar charger.	(Tsang et al., 2016)
CSP	LCA, energy and GHG	m^2	N/A	Two design guidelines are suggested: (1) Energy and GHG outperform the demand for any technological choice of photo absorber and electrocatalyst at a concentration larger than 55 kW per m^2, and (2) the system needs to be designed at an optimum concentration, i.e. the best combination of performance of the system, the relative surface of photo absorber and electrode, and irradiance.	(Dumortier and Haussener, 2015)
CST for domestic hot water	LCA	1 kWh of thermal energy	N/A	Solar hot water system is better than natural gas system in term of global warming but increase acidification and eutrophication potentials. Potential eco-design measures include material substitution e.g. replacement of copper tubes with galvanized steel tubes and recycling encouragement, for an example: increasing of the percentage of secondary aluminum in the collector frame.	(Albertí et al., 2019)
Hybrid system of STC and solar PV	LCA, CED	System	Cradle to gate	The optimal hybrid system configurations changes (e.g. increase of PV and STC area, increase the size of CHP, and minimize the grid electricity), with 12 % higher of primary energy saving, when it is considered under the life cycle perspective.	(Bahlawan et al., 2019)
Multi-junction SSC	LCA	1 kWh of electricity	Cradle to gate	The multijunction SSC is better than traditional SSC and eco-design of the cell should focus on energy efficiency.	(Blanco et al., 2020)
Solar PV	LCA	N/A	End of life	The improvement in recycling technologies has small contribution to the life cycle environmental impact.	(Ratner et al., 2020)
Battery integrated solar PV home system	Mixed integer linear programming, LCA and LCC	1 MWh of electricity	Cradle to grave	The environmental optimal system relies on battery technology, while the system is economically optimized at small size, less than 1 kW. For both economic and environmental optimization, it is essential to reduce the cost of technologies (battery and PV) and change the energy tariffs.	(Rossi et al., 2020)
HTFs for using in CSP plants	Weighted technical analysis and LCA	1 litre of HTFs	Cradle to use	The best HTF changes when considering only environmental indicators and taking into account all three aspects of technical performance, environmental impacts and price. The result also changes when the technologies are applied in other countries due to the different weight factors of the three aspects.	(Olmedo-Torre et al., 2018)

Notes: PSC: Perovskite solar cell, LCA: Life cycle assessment, OSC: Organic solar cell, SSC: Silicon solar cell, CSP: Concentrating solar power, GHG: greenhouse gas, N/A: Not available, CST: Concentrating solar thermal, STC: solar thermal collector, PV: Photovoltaics, CED: cumulative energy demand, CHP: Combined heat power, LCC: life cycle costing, HTFs: Heat transfer fluids.

analysing the environmental and economic hotspots over the life cycle of the technologies, the paper applies LCA as an eco-improvement tool, recommending some actions for the eco-design of solar energy technologies.

- Extending the concept of eco-design: Eco-design focuses on improving the environmental profiles of the technologies. In this paper, the recommended eco-design actions involve in both environmental and economic aspects by combining LCA and LCC.
- In term of (quantitative) technical results, the paper quantifies life cycle environmental impacts and costs of innovative solar PV of the NEST Spoke 1 project, and compares different choice of materials for PSCs and CSP technologies.

The paper is structured into eight main sections. Following the introduction section, the data and method section will provide detail on life cycle inventory data and methodological aspects of LCA and LCC such as functional unit, system boundary, assumptions, and life cycle impact assessment method. The main results include the life cycle impacts, environmental hotspots, from which recommended actions for the eco-design of innovative solar PV (Section 3) and CSP technologies (Section 4) will be formulated. Besides, the life cycle costing results will be presented in Section 5. Section 6 validates the results by conducting a sensitivity analysis. The discussion section provides information on the eco-design of solar energy technologies along the life cycle stages, limitations and suggestions for future work. In the conclusion section, there will be a summary of the results and research contributions. Fig. 1 present the logical flow of the paper.

2. Data and method

2.1. Description of the studied products

The studied solar PV cells include four PSCs and one OSC. The PSCs are based on either $MAPbI_2$ or CsFAMA (triple cation) perovskite layer,

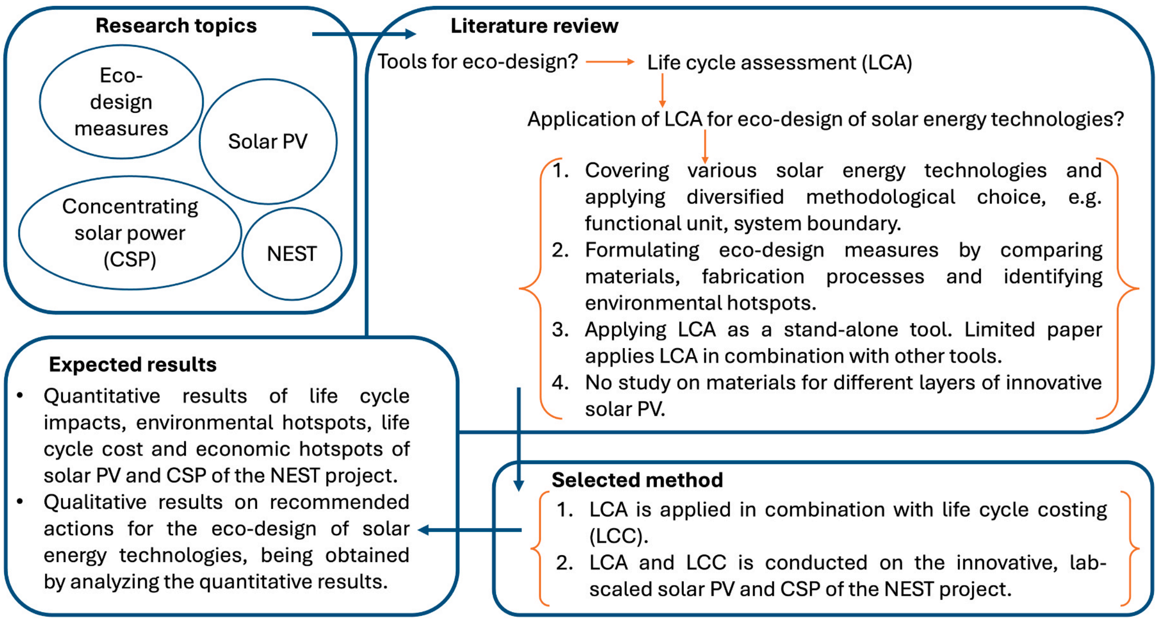

Fig. 1. Logical flow of the paper.

combined with SnO_2, SnO_2 doped Ru or TiO_2 as the electron transport layer (ETL) and hydrogenated amorphous Si, MoO_3 or SpiroOMeTAD as the hole transport layer (HTL). The OSC is made with PCBM and P3HT as absorber and PEDOT PSS as ETL on PET substrate. The studied products are presented in Table 2.

In this study, the selected CSP plants use parabolic trough and solar tower as the concentrating systems, which make up 70.7 % and 20.8 % of the installed capacity of operating CSP plants globally (Gobio-Thomas et al., 2023; NREL, 2024). These plants are equipped with thermal energy storage (TES) using molten salts as heat transfer fluids (HTFs). Two types of HTFs including solar salts ($NaNO_3$: KNO_3, at 60:40 wt% (w%)) and hitec salts ($NaNO_3$: KNO_3: $Ca(NO_3)_2$, at 15:43:42 w%) are studied. These two types of solar collectors and HTFs make up four combinations of CSP technologies, namely parabolic trough hitec salt (PTHS), parabolic trough solar salt (PTSS), solar tower hitec salt (STHS), and solar tower solar salt (STSS).

2.2. Definition of functional unit and system boundary

This study follows the ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b) for conducting LCAs on solar energy technologies to quantify and evaluate the life cycle environmental impacts. Besides, the economic aspect of the technologies is assessed with the application of LCC and the quantification of LCOE. Three different innovative solar energy technologies are studied, including PSC, OSC and CSP; however, the same product system is assessed, e.g. electricity from solar energy technologies. The selected function unit is kWh for both LCA and LCC; moreover, the functional unit of cm^2 of cell is used in complementary for analysing the environmental impacts of manufacturing lab-scaled PV cells.

For LCA, the system boundary of cradle to grave is applied with the functional unit of kWh of electricity, which considers the recycling of the PV panels and decommission of CSP plants, with some assumptions on recycling scenarios, electricity generation and lifetime of the innovative cells. Meanwhile the system boundary of cradle to gate is applied with the functional unit of cm^2 of cells for investigating the role of changing the materials, structure and fabrication process in improving the environmental profiles of the innovative, lab-scaled cells.

For LCC, the system boundary of solar PV covers the manufacturing only. The cost for operation, maintenance and end-of-life treatment is excluded because of limited data for these stages (of the innovative solar cells). Nevertheless, it is expected that the costs for operation and maintenance of innovative cells will be similar to those of conventional cells, at around 7 EUR per kWp in 2017 (Steffen et al., 2020). It is the same situation for the end-of-life treatment of innovative panels, in which the costs for mechanical treatment are similar among various panels including both panels based on silicon and ones based on innovative materials such as perovskite and organic. The costs for thermal and chemical treatment of innovative and conventional solar cells are different, with potentially higher costs for thermal and chemical treatment of innovative solar cells compared to conventional ones, due to the low technology readiness level of recycling technologies to separate the new materials. The total cost for recycling solar PV is around 28 USD per module (NREL, 2021).

For LCC of CSP, the system boundary covers the manufacturing, operation and maintenance, and excludes the cost for plant decommission due to the same reason. For both products, externalities, e.g. environmental and societal costs are excluded due to of their complexity in measuring these costs. Fig. 2 presents the functional units and environmental system boundaries of solar PV.

Table 2
PSCs and OSC of the NEST project.

Product	ENEA24	ENEA25	ENEA26	UNIPA27	UNIPA28
Type of solar cell	Perovskite solar cell	Perovskite solar cell	Perovskite solar cell	Perovskite solar cell	Organic solar cell
Substrate	FTO glass	FTO glass	FTO glass	FTO glass	ITO PET
Interlayer	MgF_2	MgF_2	MgF_2	N/A	N/A
Electron transport layer	SnO_2	SnO_2 doped Ru	SnO_2	TiO_2	PEDOT PSS
Absorber/ Active layer	$MAPbI_3$	$MAPbI_3$	CsFAMA	$MAPbI_3$	P3HT / PCBM
Hole transport layer	a-Si:H	MoO_3	MoO_3	SpiOMETAD	N/A
Electrode	Au	Au	Au	Au	Al

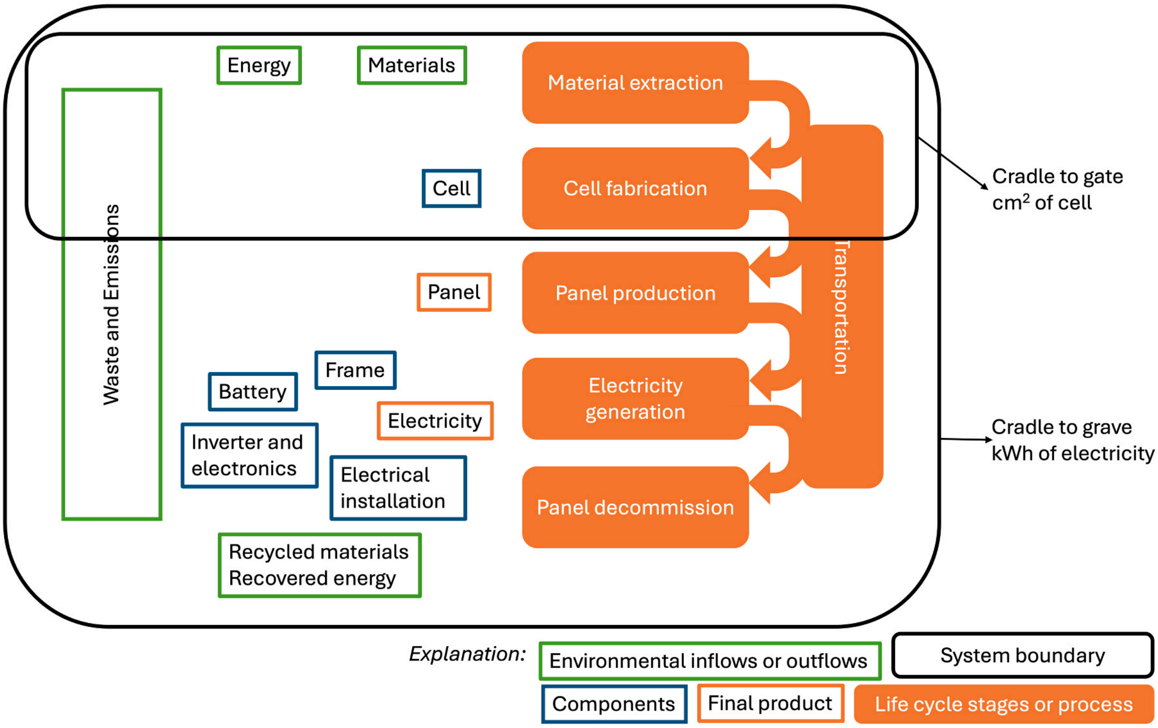

Fig. 2. Functional unit and system boundary of solar PV.

For the end-of-life treatment, due to the limited data on recycling of PSCs and OSC, the data on recycling of solar PV will be used for both innovative cells. Furthermore, the cells are studied at lab scale, and their efficiency as well as lifetime have not yet confirmed. Therefore, it is assumed that the PSCs' efficiency is 25 %, with 15 years of lifetime (IRENA, 2019; Tian et al., 2020). The efficiency and lifetime of OSC is lower, at 20 % and 5 years (Nkinyam et al., 2025; Scharber and Sariciftci, 2013).

2.3. Life cycle inventory data

The data for foreground processes of fabricating the solar PV cells are

Table 3
Main inputs and outputs for fabricating 1 cm^2 of the solar cells.

Input/ Output		Unit	Solar cells				
Layer	**Material**		**ENEA24 (PSC)**	**ENEA25 (PSC)**	**ENEA26 (PSC)**	**UNIPA27 (PSC)**	**UNIPA28 (OSC)**
Substrate	FTO glass	cm^2	6.25E+ 00	6.25E+ 00	6.25E+ 00	6.25E+ 00	
	ITO PET	cm^2					6.25E+ 00
Interlayer	MgF_2	g	7.32E-05	7.32E-05	7.32E-05		
ETL	SnO_2	g	1.98E-04		1.98E-04		
	$SnCl_4$	g		3.04E-06			
	$RuCl_3$	g		3.48E-07			
	TTIP	ml				3.65E-02	
	Isopropanol	ml				5.00E-01	
	PEDOT PSS	g					1.97E-01
Absorber	$MAPbI_3$	g	1.93E-03	1.93E-03		1.27E-01	
	$PbBr_2$	g			8.97E-08		
	FAI	g			2.01E-07		
	MABr	g			2.49E-08		
	CsI	g			4.33E-07		
	DMF	ml	2.00E-3	2.00E-3	8.89E-04		
	DMSO	ml	2.22E-4	2.22E-4	1.33E-03		
	DE	ml	2.22E-3	2.22E-3			
	Dichloromethane	ml					2.00E-01
	Chlorobenzene	ml			2.31E-03		2.00E-01
	P3HT	g					4.00E-03
	PCBM	g					2.00E-03
HTL	a-Si:H	cm^2	1.00E+ 00				
	MoO_3	g		1.56E-05	1.56E-05		
	SpiroOMeTAD	g				1.45E-02	
Electrode	Au	g	1.16E-4	1.16E-4	1.16E-4	1.16E-4	
	Al						2.12E-03
Glovebox	N_2	g	2.57E+ 02	2.57E+ 02	2.57E+ 02	2.57E+ 02	2.57E+ 02
Energy	Electricity	kWh	9.00E-02	9.26E-02	1.44E-01	4.52E-02	2.72E-02

on-site data, which was provided by the NEST project' partners from their labs. Some on-site data, which was unavailable, was taken from literature (Alberola-Borràs et al., 2018a; Anctil et al., 2020; Sánchez et al., 2019). Data for the background processes was taken from Ecoinvent database (Ecoinvent, 2020) and the International Energy Agency's life cycle inventory data (Frischknecht et al., 2020). Data on the production of specific chemicals and materials, which was used for fabricating the solar cells, was modeled based on the stoichiometric approach. The main inputs and outputs for fabricating the solar cells are mentioned in Table 3.

Data for the CSP is calculated based on the technologies installed in Palermo, Italy. Data for background processes are taken from the Ecoinvent database, with the cut-off by unit allocation method. Background processes that are not included in the Ecoinvent database, specifically the manufacturing processes of two HTFs, namely solar salts and hitec salts are modeled based on their stoichiometric approach.

2.4. Life cycle impact assessment method

Regarding the life cycle environmental impact assessment method, the product environmental footprint (PEF) of the European Commission is selected due to its suitability on assessing the environmental impacts of solar energy technologies in the European context (Khan et al., 2024; Luu et al., 2024). Apart from 16 impact categories of PEF, the study also quantifies cumulative energy demand (CED) and LCC of the technologies. The calculation of PEF's environmental impacts, CED and LCC of the technologies are presented in the Table 4.

3. LCA results and eco-design of solar PV

By quantifying the environmental impacts, identifying environmental hotspots, and comparing them to the literatures, several recommended actions for the eco-design of solar PV are proposed. First, efficiency and lifetime of the cells are important contributors to the environmental impacts of the electricity generated by solar PV; therefore, improving the efficiency of the innovative cells and lengthen their lifetime could substantially reduce their life cycle environmental impacts. Second, by changing the materials and increasing the efficiency, in both material productivity and energy efficiency, the life cycle environmental impacts can be reduced. Last, the environmental hotspots of the solar PV are identified so that the research and development effort could be focus on these hotspots for reducing the environmental impacts with the least resources.

3.1. Life cycle environmental impacts

The life cycle environment impacts and CED of solar PV per kWh of electricity from cradle to grave are presented in Table 5. The global warming potential (GWP) of PSC ranges 1.20E-01–1.56E-01 kg CO_2 eq per kWh. The human toxicity, cancer (HT-c) are between 1.25E-10 and 1.33E-10 CTUh, and the human toxicity, non-cancer (HT-nc) are from 7.19E-09–7.84E-09. Among the studied PSCs, UNIPA27 has the lowest life cycle environmental impacts, while ENEA24 has the highest impacts for most of impact categories. Considering that UNIPA27 is the reference case with similar materials and layers as a common PSC, the integration of an interlayer in innovative PSCs such as ENEA24, ENEA25 and

Table 4
Equations for quantifying PEF's environmental impacts, CED and LCC.

Impact category	Unit	Equation	Explanation	Reference
PEF's environmental impacts		$Impact_j = \sum_1^n (\sum Am_i * CF_{i,j})$	Am_i is the amount of air emissions of substance i. $CF_{i,j}$ is the characterization factors of substance i for impact j (The list of the characterization factors is accessible the European platform for life cycle assessment (EPLCA, 2018) n is the number of life cycle stages. PEF recommends two life cycle stages of raw material acquisition, pre-processing, module manufacturing and distribution. This study is conducted on lab scale technologies; therefore, distribution stage is not available. Instead, two system boundaries of cradle to gate and cradle to grave are applied as mentioned above.	(Damiani et al., 2022; EC, 2021)
Acidification potential	mol H+ eq			
Global warming potential	$kgCO_2eq$			
Ecotoxicity freshwater	CTUe			
Particulate matter formation	disease inc.			
Eutrophication potential, marine	kg N eq			
Eutrophication potential, freshwater	kg P eq			
Eutrophication potential, terrestrial	mol N eq			
Human toxicity, cancer	CTUh			
Human toxicity, non-cancer	CTUh			
Ionizing radiation	kBq U-235 eq			
Land use	Pt			
Ozone depletion potential	Kg CFC11 eq			
Photochemical ozone formation	kg NMVOC eq			
Resource use, fossils	MJ			
Resource use, metals and minerals	kg Sb eq			
Water use	m^3 depriv.			
Cumulative energy demand (CED)	MJ	$CED = \frac{(PE + Inv)}{Out_{el}}$	PE is total primary energy from the nature in MJ Inv is additional energy investment from human socio-economic activities in MJ, Out_{el} is energy delivered to society (energy output) in the unit of electricity.	(Raugei et al., 2016)
Life cycle costing (LCC)	Eur	$LCC = \sum_m^n (\mu_m * \sum Am_{ij} * uCost_{i,j})$	$Am_{i,j}$ is the amount of input consumed or output recycled (treated) i and j. $uCost_{i,j}$ is the unit cost of input or output i,j m is process, μ_m is the coefficient of process contribution to the life cycle cost. n is the life cycle stages. Due to the limitation of data, this study quantifies the costs during manufacturing stage only. Besides no externality is included in the calculation.	(Rebitzer and Nakamura, 2007)

Notes: PEF: Product Environmental Footprint, CED: Cumulative Energy Demand, LCC: Life Cycle Costing

Table 5
Life cycle environmental impacts and CED of solar PV per kWh from cradle to grave.

Impact category	Unit	ENEA24	ENEA25	ENEA26	UNIPA27	UNIPA28
AP	mol H+ eq	1.13E-03	1.08E-03	1.08E-03	9.64E-04	2.77E-03
GWP	kg CO_2 eq	1.56E-01	1.48E-01	1.48E-01	1.20E-01	3.59E-01
ET-fw	CTUe	2.29E+ 00	2.26E+ 00	2.26E+ 00	2.33E+ 00	2.26E+ 00
PMF	disease inc.	9.53E-09	9.04E-09	9.04E-09	8.66E-09	2.61E-08
EP-m	kg N eq	1.51E-04	1.42E-04	1.42E-04	1.30E-04	3.10E-04
EP-fw	kg P eq	1.28E-04	1.24E-04	1.24E-04	1.21E-04	8.59E-05
EP-t	mol N eq	1.72E-03	1.62E-03	1.62E-03	1.45E-03	3.39E-03
HT-c	CTUh	1.33E-10	1.27E-10	1.27E-10	1.25E-10	2.81E-10
HT-nc	CTUh	7.84E-09	7.66E-09	7.66E-09	7.19E-09	9.13E-09
IR	kBq U-235 eq	2.41E-02	2.34E-02	2.34E-02	1.95E-02	6.42E-02
LU	Pt	5.99E-01	5.74E-01	5.74E-01	4.65E-01	9.96E-01
ODP	CFC11 eq	1.18E-08	1.18E-08	1.18E-08	1.15E-08	1.25E-07
PCOF	kg NMVOC eq	5.55E-04	5.29E-04	5.29E-04	4.58E-04	1.15E-03
RU-f	MJ	2.44E+ 00	2.34E+ 00	2.34E+ 00	1.97E+ 00	5.98E+ 00
RU-m	kg Sb eq	1.55E-05	1.54E-05	1.54E-05	1.61E-05	8.12E-06
WU	m^3 depriv.	6.48E-01	6.42E-01	6.42E-01	7.68E-01	1.38E+ 00
CED	MJ	6.89E+ 00	6.78E+ 00	6.78E+ 00	6.21E+ 00	1.09E+ 01

Notes: AP: Acidification potential, GWP: Global warming potential, ET-fw: Ecotoxicity, freshwater; PMF: Particulate matter formation; EP-m: Eutrophication, marine; EP-fw: Eutrophication potential, freshwater; EP-t: Eutrophication, 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, metals and minerals; WU: Water use; CED: Cumulative energy demand.

ENEA26, and the complexity in the manufacturing of their ETLs cause an increase in their environmental impacts. Besides, the increase is small and insignificantly different among three innovative PSCs. It should be noted that all studied PSCs have the same efficiency and lifetime, i.e. the technical improvements of the innovative cells' interlayers and ETLs are not taken into consideration. In case the technical improvements of the innovative PSCs are included, it is expected that their environmental impacts per kWh will reduce and be competitive with the reference PSC. For OSC, the GWP is 3.59E-01 kg CO_2 eq per kWh. Its HT-c and HT-nc are 2.81E-10 and 9.13E-09 CTUh, respectively. Generally, the life cycle environmental impacts and CED of OSC are higher than those of PSCs.

3.2. Recommended action 1: improving efficiency and lifetime of the cells

The first recommended eco-design action is to improve the efficiency and lifetime of the solar cells. This recommended action is concluded based on the comparison of environmental impacts of the solar cells per cm^2 and kWh. Fig. 3 compares the main life cycle environmental impacts of solar PV cells per cm^2 and per kWh. As being illustrated in Fig. 3a, the life cycle environmental impacts of OSC per cm^2 of cell is much lower than those of PSC, at average, for all indicated impact categories. For examples, the GWP and resource use, fossils (RU-f) of OSC are 3.98E-02 kgCO_2eq and 7.31E-1 MJ per cm^2, which are 1.7 and 1.6 times lower than the average values of PSCs, at 6.85E-02 kgCO_2eq and 1.15E+ 00 MJ, respectively. The largest difference is in resource use, metals and minerals (RU-m). RU-m of PSC ranges from 7.09E-06–7.73E-06 kg Sb eq per cm^2, being at 7.33E-06 kg Sb eq at average. This average number is nearly 30 times higher than that of OSC, at 2.47E-07 kg Sb eq per cm^2. Other life cycle environmental impacts and CED of solar PV per cm^2 of cell from cradle to gate are provided in the supporting information table SI1.

In contrast, the life cycle environmental impacts of OSC per kWh are higher than those of PSCs for most impact categories, as can be seen in Fig. 3b. The GWP of OSC is 3.59E-01 kgCO_2eq kWh, which doubles that of PSC at 1.43E-01 kg CO_2 eq on average. Similarly, the RU-f impact of OSC at 5.98 MJ, which is 2.6 times higher than that of PSC, with the range from 1.97 to 2.44 MJ. CED of OSC is 10.89 MJ which is 1.6 times higher than the average value of PSCs, ranging from 6.21 to 6.89 MJ. The HT-c and HT-nc impacts of OSC are 2.2 and 1.2 times higher than the average values of PSCs. The contradictory results of Fig. 3a and Fig. 3b indicate the role of efficiency and lifetime of the solar PV cells on their life cycle environmental impacts. While the OSC has a better environmental profile compared to PSCs per cm^2, it may not be the better option considering the impacts per kWh of electricity. This is due to the short lifetime of OSC, and its lower efficiency compared to those of PSCs.

Furthermore, this recommended action was supported by comparing the life cycle environmental impacts of OSC in this study and in the literature. The results obtained by (Tsang et al., 2016) per kWh of electricity from OSC are considerably higher than those of this study. Specifically, GWPs of OSC range from 5.42E+ 02–6.94E+ 02 per kWh, depending on end-of-life treatment strategies (i.e. incineration or landfill) and types of OSC module (i.e polymer based bulk heterojunction or all polymer) (Tsang et al., 2016). Similarly, the CED of (Tsang et al., 2016)'s study is a thousand times higher than the obtained result of this study. The large difference between the two studies likely originates from the different assumptions on efficiency of the OSC. While (Tsang et al., 2016) assumed 5 % of efficiency, 5 years of lifetime and 25 years of operation, this study quantified the environmental impacts and CED with higher efficiency (20 %) and 5 years of lifetime and operation. The high efficiency and the same lifetime and operation duration in this study considerably reduce the environmental impacts of the cells per kWh compared to those in the literature. This comparison again highlights the role of efficiency and lifetime of the cells in improving the environmental profile of OSC, in which by improving the efficiency and lifetime of the cells, the life cycle environmental impacts per kWh could be reduced.

3.3. Recommended action 2: changing materials and fabrication processes

The second eco-design recommended action is to select the appropriate materials and fabrication process. The quantifications of life cycle environmental impacts and CED indicate that PSCs have better environmental profiles compared to OSC (Section 3.1) due to OSC's low efficiency and short lifetime. Therefore, for the applications which does not require long lifetime such as small electronics, portable devices, the eco-design actions may cover organic materials. Meanwhile, the eco-design of solar PV at the larger scale should focus on solar cells based on perovskite materials. Among innovative PSCs, the choices of following materials are encouraged in terms of environmental profiles:

- SnO_2 doped Ru is slightly better than SnO_2 as ETL,
- $MAPbI_3$ is better than CsFAMA as absorber,
- MoO_3 is better than a-Si:H as HTL, and

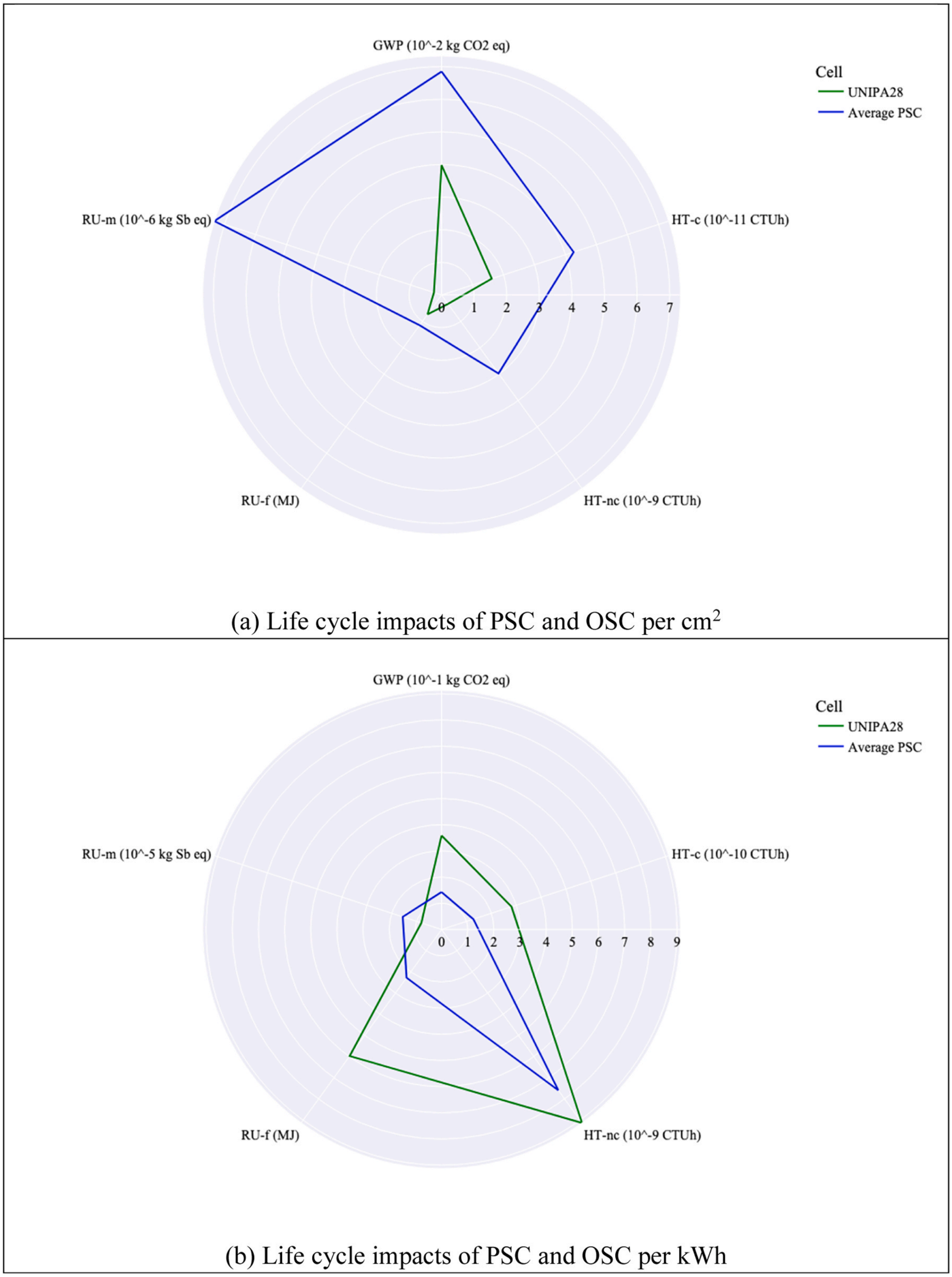

Fig. 3. Comparison of life cycle environmental impacts of PV cells.

- The combination of SnO_2 doped Ru, $MAPBI_3$ and MoO_3 (ENEA25) and SnO_2, CsFAMA and MoO_3 (ENEA26) are better than SnO_2, $MAPBI_3$ and a-Si:H (ENEA24).

The solar PV in this study seems to have a better environmental profile compared to similar products being manufactured at the lab scale. Specifically, the GWP of lab-scale PSC, with carbon stack cathode, is 9.50E+ 00 kg CO_2 eq per kWh (Alberola-Borràs et al., 2018a), which is considerably higher than the average GWP of PSCs in this study. Besides, CEDs of PSCs in this study are lower than the lab-scaled PSC in (Alberola-Borràs et al., 2018a), at 2.31E+ 02 MJ per kWh. This comparison indicates that the choice of materials and fabrication process of the studied PSCs, especially the new ENEA PSCs, with the integration of interlayer, absorber layers and ETLs show the environmental benefits with lower impacts per kWh compared to the similar counterpart.

Besides, there is a potential to reduce the environmental impacts of the PSCs if the cells are manufactured at industrial scale. Case studies on similar PSCs indicated that the GWP may reduce by half to 5.63E-02 or 7.69E-02 kg CO_2 eq (Alberola-Borràs et al., 2018b), and CED even reduce by 4.5–6.5 times to 1.03E+ 00 or 1.46E+ 00 MJ (Alberola-Borràs et al., 2018b, 2018a) by upscaling the production. Furthermore, by changing both production scale, fabrication process and choice of materials simultaneously, the GWPs of PSCs may reduce up to 45 times. For examples GWPs of PSC may reduce to 3.01E-02 kg CO_2 eq (Alberola-Borràs et al., 2018a) by using carbon stacked for cathode and upscaling the production, to 3.00E-02 kg CO_2 eq (Sánchez et al., 2019) by changing the fabrication process from antisolvent into flash infrared annealing, or to 3.13E-03 kg CO_2 eq by replacing the common electrode into the graphene transparent one (Li et al., 2022). The same reduction patterns are expected for CED and other environmental impacts such as ecotoxicity, freshwater (ET-fw), HT-c, HT-nc, RU-f and RU-m.

The comparison of GWP and CED of PSC in this study with those in the literature (being illustrated in Fig. 4) indicates that choice of materials and change in fabricating process will improve the environmental profiles of the solar cells. Some materials such as graphene can be used as electrode in replacement of critical raw materials such as gold. Similarly, carbon can be used as cathode in PSC. In other cases, the improvement of fabricating process such as applying flash infrared annealing or inkjet printing for depositing the absorber layer, in replacement of the common process using antisolvent with spin coating and thermal annealing may help to reduce the environmental impacts and CED of PSCs per kWh of electricity.

This is the same case for OSC in which the environmental impacts may reduce significantly by upscaling the production and changing the materials. In the case study of Li et al., the CED of OSC with graphene transparent electrode was quantified at 1.67E-01 MJ per kWh (Li et al., 2022), which is considerably lower than the CED of OSC in this study. Similarly, there is a significant difference in the GWP, RU-f and RU-m between the two studies. Although there are several differences in the assumptions in the two LCA studies, it is likely that the large variance, up to ten times, in obtained results originates from the scale of production. The variance suggests that the impact from this lab-scaled OSC could be reduced when it is manufactured at large scale. Changing the material, for an example using graphene as electrode may help to further reduce the environmental impacts.

3.4. Environmental hotspots and recommended action 3: reducing environmental impacts of electron transport layer, absorber and electrode

The hotspot analysis points out that glovebox, ETL, absorber and electrode are among the top contributors of the environmental impacts of PSCs for most of the impact categories. The interlayer of MgF_2, which aims to improve the efficiency of the PSC has inconsiderable impacts to the overall environmental profile of the cells. Regarding types of resources, the majority of impacts come from material and electricity consumption, while transportation contribute to negligible shares of the total impact.

Fig. 5 illustrates the contribution of layers and types of resources to GWP, RU-f and RU-m of the solar PV. For GWP and RU-f (Figs. 5a and 5b), glove box accounts for 33 % of the impacts of ENEA24 and ENEA25, 27 % in ENEA26 and 45 % in UNIPA27. This is mainly caused by the use of nitrogen in the glovebox, while electricity consumption for the glove box contributes to a small share. ETL is responsible for around 30 % (and above) of the impacts for innovative PSCs and 25 % of the impacts for conventional PSC, which is due to the electricity consumption for depositing the ETL. The absorber layer of ENEA26 contributes to 28 % of GWP and CED, because of the energy intensiveness of the CsFAMA absorber layer in ENEA26, which requires more energy for spin coating and annealing, compared to other perovskite materials, while it is not an environmental hotspot for other PSCs.

In term of RU-m (Fig. 5c), electrode is the main cause of the impact for all PSCs, rooting from the use of gold for the electrode, with relatively high impact factor compared to other metals, for example aluminum in OSC. This result aligns with the existing literature in which gold electrode has been identified as the main contributor of life cycle material consumption for PSCs (Zhang et al., 2017).

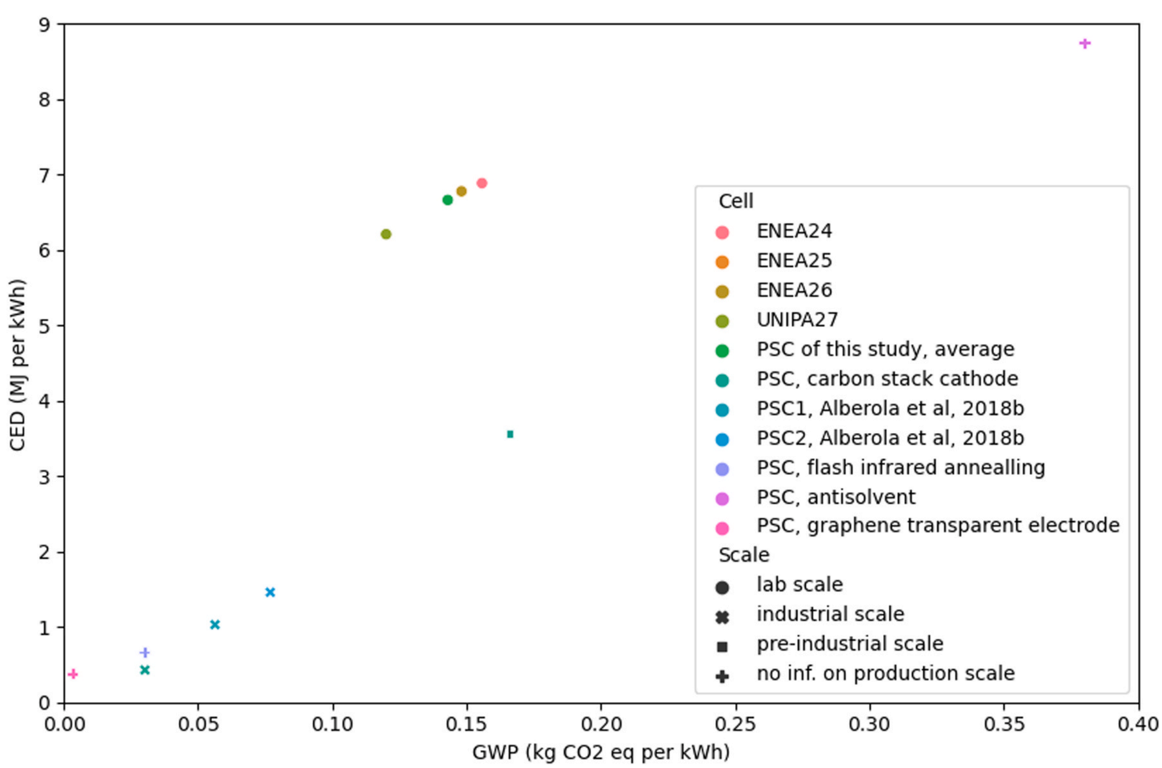

Fig. 4. Comparison of GWP and CED of PSCs in this study and in the literature.

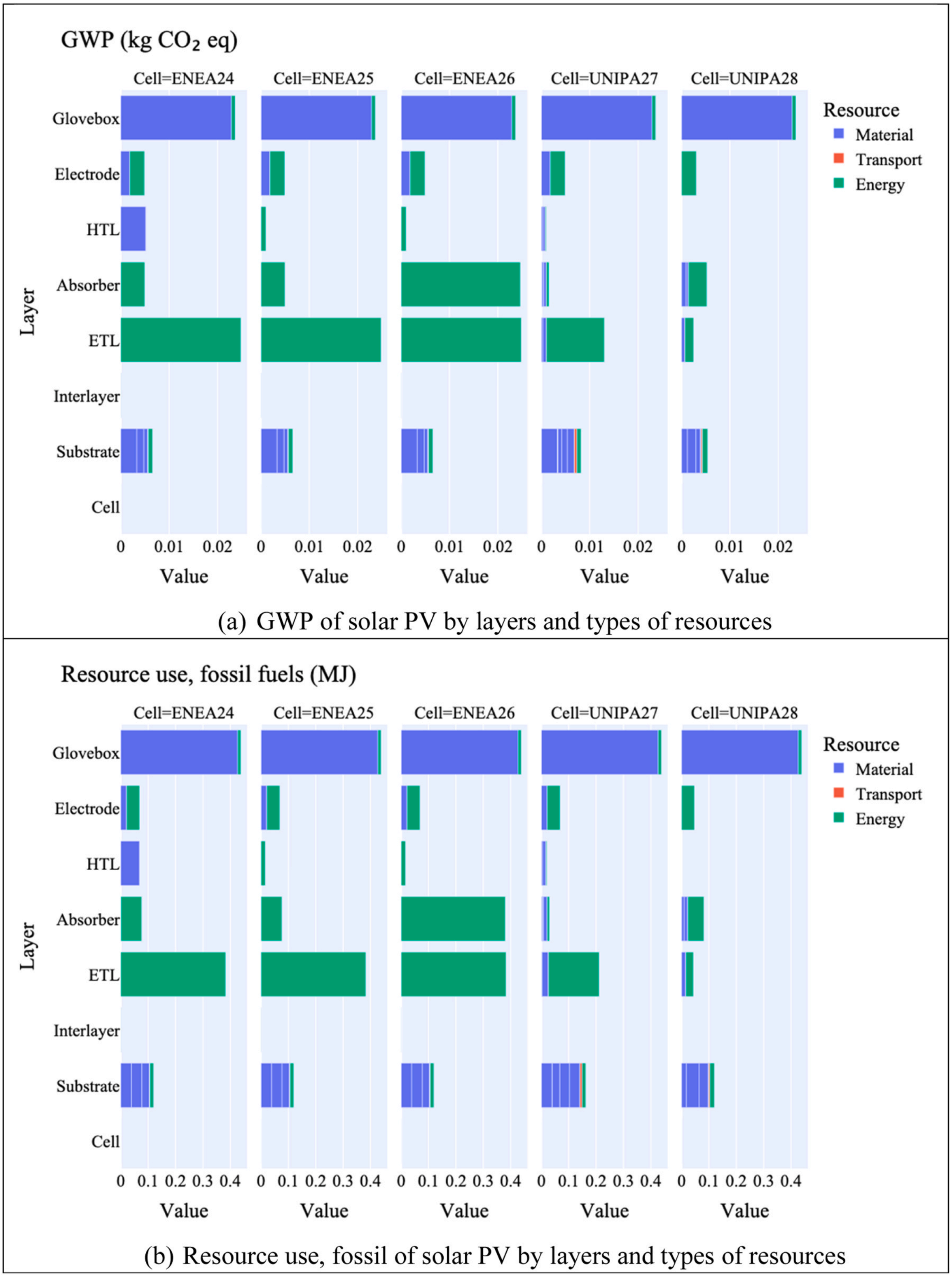

Fig. 5. Share of impacts by layers of solar PV cells.

The same hotspots are identified for OSC, but the shares of impacts by layers are different. Glove box is the largest contributor for most of the impact categories, ranging from 49 % to 80 %, namely acidification potential (72 %), eutrophication potential, marine (EP-m) and terrestrial (EP-t) (56 %), GWP (59 %), ionizing radiation (80 %), photochemical ozone formation (49 %), particulate matter formation (77 %), and RU-f (59 %) (see Fig. 5d). This is mainly due to the consumption of nitrogen to create an inert environment in the glovebox for fabricating the solar PV cells. The use of electricity in the glovebox is negligible compared to the use of nitrogen gas. Considering only the layers of the solar cell, the absorber layer and substrate are the main contributors for several impacts. The absorber layer accounts for 70 % of ozone

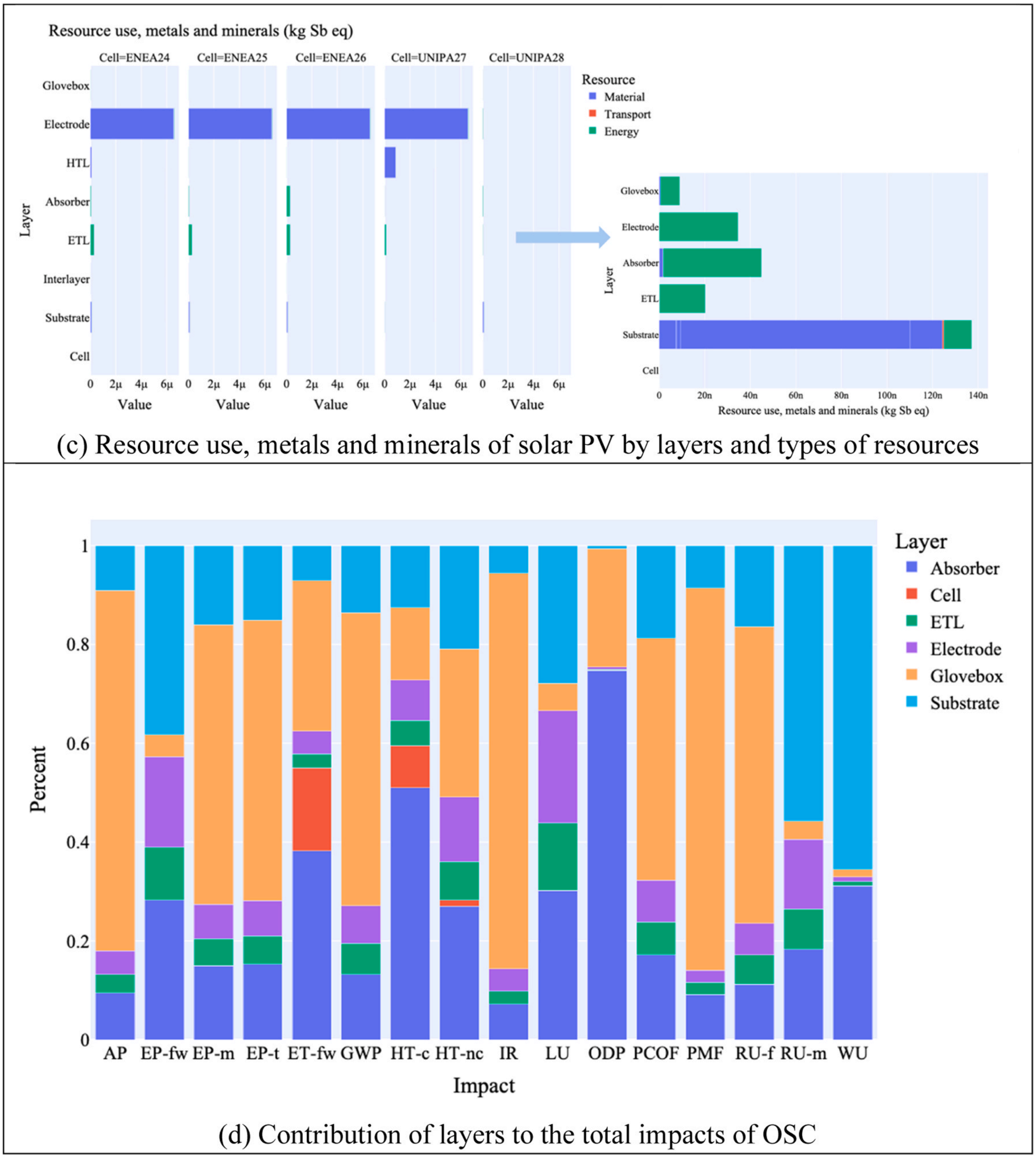

Fig. 5. (*continued*).

depletion potential (ODP), 51 % of HT-c, 38 % of ET-fw, 30 % of land use, 28 % of EP-fw and 27 % of HT-nc, and being the largest contributors of ODP, HT-c and ET-fw. The substrate layer is the top contributor of water use (65 %), RU-m (55 %) and EP-fw (38 %). The share of impacts among layers, types of resources and materials for all studied solar PV cells can be found in the supporting information table SI2.

It is recommended that the eco-design of PV cells should focus on electrode layer of PSC, and absorber layer of OSC and substrate layer of both PSC and OSC. The material for these layers should be further studied, in relation with energy consumption for fabricating this layer, as the change in the materials will induce change in energy requirement for fabricating processes. Besides, it is recommended that the process of fabricating the cells, for both PSC and OSC should be improved, due to the considerable contribution of glove box to the total impact.

4. LCA results and eco-design of CSP

The recommended eco-design actions for CSP technologies are suggested based on the quantification of the life cycle environmental impacts and comparing them to the literature. First, the solar radiation is an important factor to the life cycle environmental impacts of CSP, which suggests the careful selection of location and other relevant technical conditions for installing the plants. Second, the CSP plants frequently includes the solar-to-power and fossil fuel components, e.g. natural gas for cogeneration and auxiliary purposes, consequently, the eco-design of CSP technologies should cover both these two components, through minimizing the use of natural gas, replacing it with other low-impact fuels and reducing the impacts of some environmental hotspots among solar-to-power component.

4.1. Life cycle environmental impacts

The life cycle environmental impacts and CED are calculated for four CSP technologies, including PTHS, PTSS, STHS, and STSS (as included in the supporting information table SI3). The GWPs of CSP range from 7.46E-02–8.36E-02 kg CO_2 eq per kWh, with the highest value being originated from PTHS, and the lowest value from STSS. ET-fw impacts are between 1.94E-01 and 6.29E-01 CTUe per kWh, with the same order from the highest value of PTHS to the lowest value of STSS. Generally, parabolic trough CSP plants cause larger environmental impacts than solar tower CSP (see Table 6). This occurs in most impact categories, expect for HT-c, HT-nc and land use. The differences in environmental impacts of the two technologies are obvious in some impacts such as ET-fw, EP-m and EP-t. ET-fw of parabolic trough CSP triples that of solar tower, and EP-m and EP-t of parabolic trough CSP double those of solar tower. Meanwhile, for some impacts such as GWP, HT-c, RU-f and RU-m, the differences are inconsiderable (less than 12 %). Comparing the HTFs, solar salts CSP plants have lower impacts than hitec salts CSP for most of the impact categories, except for EP-m and photochemical ozone formation. The differences between the environmental impacts of the two HTF are negligible (around 1 %), except for the case of water use, in which hitec salt CSP plants consume water twice as much as solar salts CSP (see Table 6).

4.2. Recommended action 1: optimizing the plant configurations for the best solar radiation and lowest life cycle impacts

Being compared to the literature, the average CED and environmental impacts of CSPs in this study are higher than those of (Burkhardt et al., 2011) for different designs of parabolic trough CSP such as wet cooling or dry cooling, with mined nitrate salts or synthetic salts as HTF, and two tank or thermocline TES, and (Whitaker et al., 2013) for different design of solar tower CSP such as dry cooling with mined nitrated salt and electricity grid for auxiliary, or synthetic salts, thermocline based TES and natural gas used for auxiliary. The CEDs of CSPs in this study are from 1.11 to 1.23 MJ which is nearly three times higher than those of (Burkhardt et al., 2011) and (Whitaker et al., 2013). Similarly, GWPs of CSP in this study, at 7.98E-02 kg CO_2 eq on average, are around 2.5 times higher than the average value of (Burkhardt et al., 2011) and (Whitaker et al., 2013), at 3.08E-02 kg CO_2 eq. Although applying different plant designs, the CSP plants in (Burkhardt et al., 2011) and (Whitaker et al., 2013)'s studies were located in areas with high solar radiation, at 2700 kWh/m^2/yr and 2600 kWh/m^2/yr, respectively. This comparison indicates that the CED and environmental impacts of the CSP largely depends on the location of the plant, with relevant solar radiation and other technical conditions. In such case, the selection of location for constructing the CSP plant is crucial for maximizing the productivity of the plant, e.g. energy yield, while minimizing its environmental impacts.

Table 6
Life cycle environmental impacts per 1 kWh of electricity from CSP.

Impact category	Unit	Parabolic trough CSP	Solar tower CSP	Hitec salt CSP	Solar salt CSP
AP	mol H+ eq	3.54E-04	2.77E-04	3.18E-04	3.13E-04
GWP	kg CO_2 eq	8.31E-02	7.50E-02	7.95E-02	7.86E-02
ET-fw	CTUe	6.29E-01	1.95E-01	4.13E-01	4.11E-01
PMF	disease inc.	3.62E-09	2.66E-09	3.16E-09	3.12E-09
EP-m	kg N eq	9.28E-05	4.39E-05	6.81E-05	6.86E-05
EP-fw	kg P eq	1.27E-05	1.08E-05	1.18E-05	1.17E-05
EP-t	mol N eq	9.79E-04	4.84E-04	7.43E-04	7.20E-04
HT-c	CTUh	1.08E-10	1.11E-10	1.10E-10	1.09E-10
HT-nc	CTUh	6.49E-10	7.93E-10	7.26E-10	7.16E-10
IR	kBq U-235 eq	1.74E-03	1.26E-03	1.59E-03	1.42E-03
LU	Pt	3.45E+ 00	3.98E+ 00	3.73E+ 00	3.70E+ 00
ODP	CFC11 eq	3.78E-09	2.69E-09	3.25E-09	3.22E-09
PCOF	kg NMVOC eq	3.32E-04	2.13E-04	2.71E-04	2.73E-04
RU-f	MJ	1.10E+ 00	9.83E-01	1.04E+ 00	1.04E+ 00
RU-m	kg Sb eq	4.42E-07	4.10E-07	4.36E-07	4.16E-07
WU	m^3 depriv.	4.28E-02	2.38E-02	4.82E-02	1.84E-02
CED	MJ	1.23E+ 00	1.11E+ 00	1.17E+ 00	1.17E+ 00

Notes: AP: Acidification potential, GWP: Global warming potential, ET-fw: Ecotoxicity, freshwater; PMF: Particulate matter formation; EP-m: Eutrophication, marine; EP-fw: Eutrophication potential, freshwater; EP-t: Eutrophication, 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, metals and minerals; WU: Water use; CED: Cumulative energy demand.

4.3. Recommended action 2: minimizing the use of natural gas

The analysis on environmental hotspots indicates that the natural gas consumption for cogeneration and as the auxiliary fuel is the largest contributor for several impacts, including GWP, ODP (from 55 % to 82 %) and RU-f. Specifically, the process of heat generation from natural gas in CSP plants contributes to more than 55 % of the impacts, depending on the concentrating technologies and impacts. The contributions of natural gas and the energy production processes related to natural gas are slightly different among concentrating technologies, for examples, at 60 % and 72 % of RU-f for parabolic trough and solar tower technologies, respectively. For GHG, 55 % of the impact comes from natural gas and related processes for parabolic trough technologies, and up to 65 % for solar tower technologies. Besides, natural gas and related processes contribute from 55 % to 82 % of ODP. The results are supported by several studies, which confirmed that the natural gas hybridized CSP has higher impacts in terms of GWP, RU-f, land use and acidification than solar only CSP plants (Corona et al., 2014).

At the same time, the more natural gas being consumed in CSP plants, the worse their environmental profiles. For examples, with 35 % of co-generation from natural gas, the CEDs of co-generation CSP in the literature range from 5.92E+ 00 MJ to 8.48E+ 00 MJ (Corona et al., 2014), which is higher than CEDs of CSP plants obtained in this study. Similar pattern was identified for other environmental impacts, in which GWPs of these CSP plants are from 3.11E-01–3.92E-01 kg CO_2 eq (Corona et al., 2016, 2014), being much higher than GWPs of CSP in this study, ranging from 7.46E-02–8.36E-02 kg CO_2 eq. In contrast, by minimizing the use of natural gas, for examples using natural gas for auxiliary consumption only, natural gas contribution of up to 2 % of co-generation, or replacing natural gas with mixed manure biogas, biowaste biogas, GWPs reduce to 1.01E-02 and 6.83E-02 kg CO_2 eq (Pelay et al., 2020; San Miguel and Corona, 2014), which are lower than the average GWP of CSP in this study. This comparison points out the large contribution of natural gas to the CED and environmental impacts of CSP. By minimizing natural gas and replacing with other low-impact fuels such as biogas and biomass, the CEDs and environmental impacts of the CSP can be reduced.

4.4. Environmental hotspots among solar-to-power components and recommended action 3: reducing environmental impacts of collector field, power generation unit and heat transfer fluid

The contributions of solar-to-power components of CSP plants such as collector field, HTF, power generation units, TES, to the individual impacts are less than 15 % each, except for the case of solar collectors of STSS. The contributions of each component are illustrated in Fig. 6 for GWP, RU-f, RU-m and ET-fw. The detailed share of each component for all impacts can be found in the supporting information table SI4. It should be noted that the component named "Natural gas" in Fig. 6 and

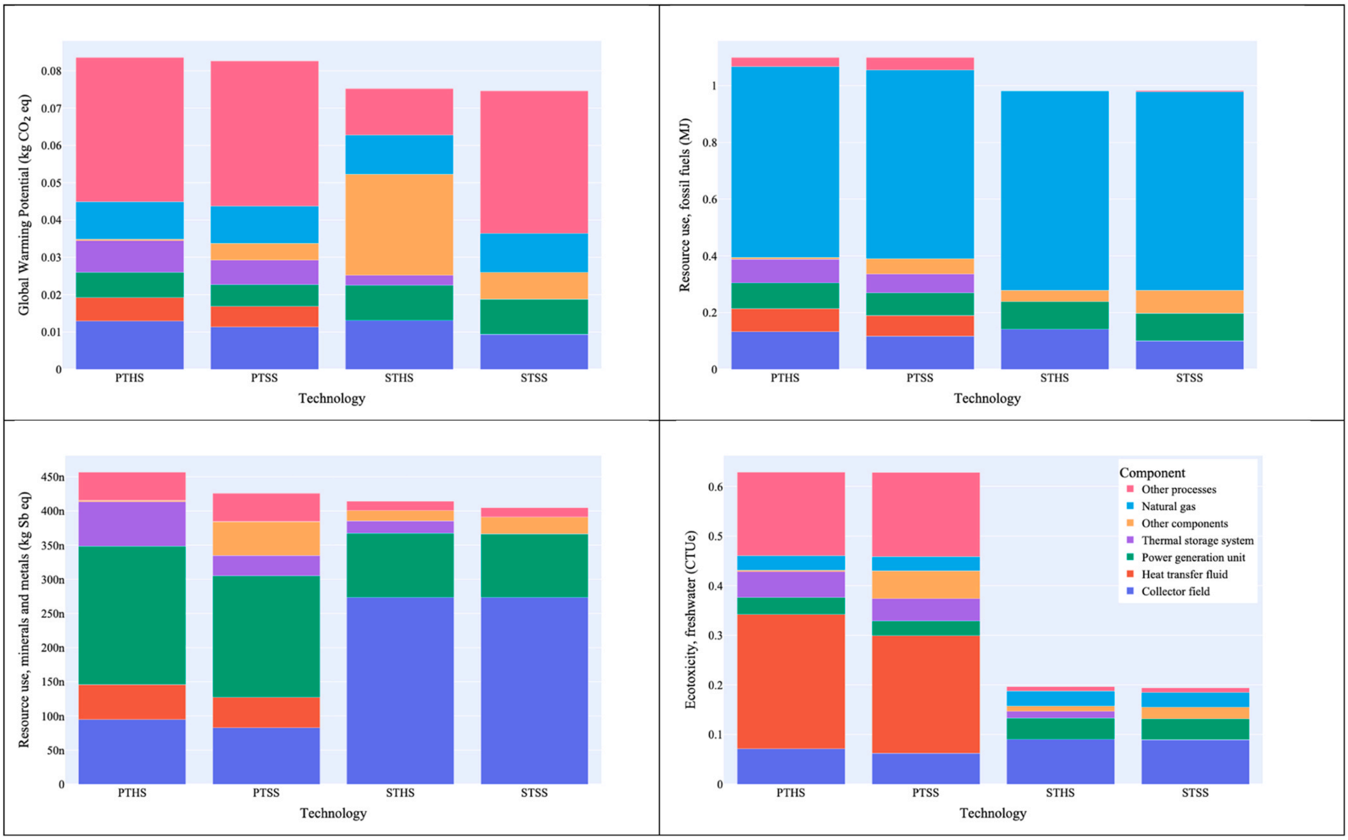

Fig. 6. Share of main impacts by components of CSP.

Table SI4 only includes impact from natural gas itself and excludes impact from other processes related to natural gas. Other processes related to natural gas are expressed in "Other processes".

The contributions of these components are different among technologies and impacts. Specifically, in term of GWP, the contribution of solar collector is highest in STSS technology, accounting for 34.8 %, which is followed by PTHS (15.5 %) and PTSS (13.7 %) and being lowest with STHS (12.5 %). Regarding RU-f, collector field contributes to 12.1 % of the total impact of PTHS, and around 10.5 % for PTSS and STHS technologies. It only contributes to 5.3 % of the total impacts of RU-f in STSS technology. Apart from natural gas, it is confirmed that collector field is the main contributor to the GWP and RU-f of all four technologies.

Most of the RU-m originates from the collector field and power generation unit. Collector field contributes from 19 % to 68 % of RU-m. Power generation unit contributes from 23 % to 44 %, depending on the specific technologies.

Regarding toxicity impacts, the hotspots lie in collector field for both HT-c and HT-nc. Specifically, collector field contributes 55 % to 64 % of HT-c. This range depends on technologies, with the lower end coming from parabolic trough technologies and the higher end coming from solar tower technologies. For HT-nc, collector field contributes to about 26 %-27 % for parabolic trough technologies, and around 58 %-60 % for solar tower technologies. For ET-fw, the identified hotspots are HTF and collector field. For parabolic trough, HTF is the top contributors, accounting for 43 % of ET-fw for PTHS and 38 % for PTSS technologies. For solar tower technologies, collector field holds the largest share of this impact, contributing from 46 % to 67 %.

5. Life cycle costing results of solar energy technologies

Life cycle cost of PSCs and OSC range from 8.16 to 32.9 EUR per cm^2 (as presented in Table 7). The most expensive cell is ENEA27 PSC, at 32.9 EUR per $cm^{2.}$ The innovative PSCs are four times more expensive than the reference PSC (UNIPA27), at 8.16 EUR per cm^2. The cost for OSC (UNIPA 28) is in between, at 17 EUR per cm^2. In all cases, the costs of lab-scaled cells are extremely more expensive than the silicon- based commercial solar cells, at less than 3.6 EUR per cm^2 of panel (Ogletree, 2025).

LCOE(s) of PSCs and OSC range from 11 EUR to 59.8 EUR per kWh. The PSCs of ENEA have the highest LCOE(s) at around 59 EUR per kWh, due to the high cost per cm^2 of cell. Meanwhile the LCOE of UNIPA's PSC which is the reference case, is four time less expensive, at 14.6 EUR per kWh. LCOE of OSC (UNIPA 28) is the lowest, at 11.4 EUR per kWh. From the economic point of view, OSC is the best solar PV; however, its life cycle environmental impacts are the highest for most of impact

Table 7
LCC of cells and LCOE from solar energy technologies.

Cost component	Unit	ENEA24	ENEA25	ENEA26	UNIPA27	UNIPA28
Material	EUR per cm^2	31.5	32.5	32.9	8.16	17.0
Energy	EUR per cm^2	0.0108	0.0111	0.0173	0.00544	0.00327
Transport	EUR per cm^2	1.30E-05	1.30E-05	1.30E-05	8.18E-04	4.24E-04
Total cost	EUR per cm^2	31.5	32.5	32.9	8.16	17.0
Total cost	EUR per kWh	58.0	59.8	59.8	14.6	11.4

categories. In contrast, the PSCs cause the lower environmental impacts, but require the larger manufacturing costs and LCOE. This is a trade-off between the economic aspects and the environmental impacts of the innovative solar cells, in which the economic advantage sometimes has to scarify for environmental protection and vice versa.

Compared to LCOE of solar PV which is at 4.4 US cents per kWh for the global average, utility-scaled system, from 9 to 22 Euro cents per kWh for small battery PV system and 7–16 Euro cents for larger battery PV rooftop system (IRENA, 2024; Kost et al., 2024), the LCOEs of these innovative solar PV are too expensive and far from the market readiness in term of cost. However, it should be noted that all the studied innovative cells are fabricated at lab scale, meaning that there is space for further reducing the environmental impacts, manufacturing cost and LCOEs, while improving their efficiency, lifetime and other technical characteristics.

The LCOEs of electricity generated from CSP plants in this study are considerably different among technologies. LCOE of parabolic trough is at 0.62 USD per kWh, being equivalent to 0.58 EUR per kWh. There is a large difference between technologies, with the considerably expensive compared to solar tower technologies, at 0.1 USD per kWh, or 0.08 EUR per kWh. This is caused by the high installation cost of the parabolic trough technology, due to higher installed capacity of parabolic trough compared to solar tower (50 MW vs 20 MW).

Fig. 7 presents the contribution of installation, operating and maintenance costs of CSP technologies. Most of the cost is spent on capital investment, up to 95 % for parabolic trough and 76 % for solar tower. Solar field (in case of parabolic trough) and heliostat field and tower (in case of solar tower) contribute a large part of the installed cost, with 28 % for solar field, 19 % for heliostat field and tower. Another top contributor is the power block, accounting for 17 % of the installed cost of parabolic trough and 10 % of solar tower. HTF and TES together account for 24 % and 17 % of total cost of parabolic trough and solar tower, respectively. The operating and maintenance costs account for a small share of the total cost.

6. Sensitivity analysis

The most recent research on PSCs of the University of New South Wales indicated that the cells' efficiency may reach 27 % (NREL, 2025); therefore, a sensitivity analysis is conducted on the efficiency fluctuations of PSCs, in which their efficiency increases from 25 % to 27 %. In this case, all the impacts reduce accordingly. All life cycle environmental impacts reduce by 8 % for all the studied PSCs. The proportional reductions are the same among all life cycle environmental impacts and four studied PSCs, because the cells' efficiency will affect the required amounts of cells (in m^2), which reduce at the same rate for all PSCs. Meanwhile, the CEDs reductions are different among PSCs, ranging from 2.9 % to 3.4 %. The largest reduction originates from ENEA24, and the smallest reduction comes from UNIPA27. CED, non-renewable energy and CED, renewable energy from biomass and water reduce by 8 % each. The CED, renewable energy from solar does not change much because the majority part of CED, renewable energy from solar is consumed for electricity generation, and this amount, e.g. the amount of solar radiation reaching the cells does not change, in case the efficiency increases. Fig. 8 presents the reductions of life cycle environmental impacts when the efficiency of the cells increases from 25 % to 27 %.

7. Discussion

The recommended eco-design actions mainly focus on the manufacturing processes of solar energy technologies, because most of the environmental impacts and costs originate from these processes. However, there is a potential to integrate the environmental and economic aspects into other life cycle stages such as transportation, consumption, use and end-of-life treatment. For the transportation, the impact will reduce in case the manufacturing sites are close to the material storages. For consumption and use, the supply of information to the user is crucial to the efficient use of the systems, especially for those being installed in the household such as PV rooftop and residential solar heating and cooling system. This affects the maintenance of the system to extend the lifetime of solar energy technology, and the selected end-of-life treatment strategies of the systems. Besides, it is important to consider the whole life cycle, e.g. the link between life cycle stages such as transportation, manufacturing and end-of-life treatment. Recycling the solar PV may reduce the material demand, but it does not ensure the reductions in life cycle environmental impacts, especially in case the recycling process is energy intensive, or the recycling factory is far from the location of solar PV plants.

The paper covers two main solar energy technologies, e.g. solar PV

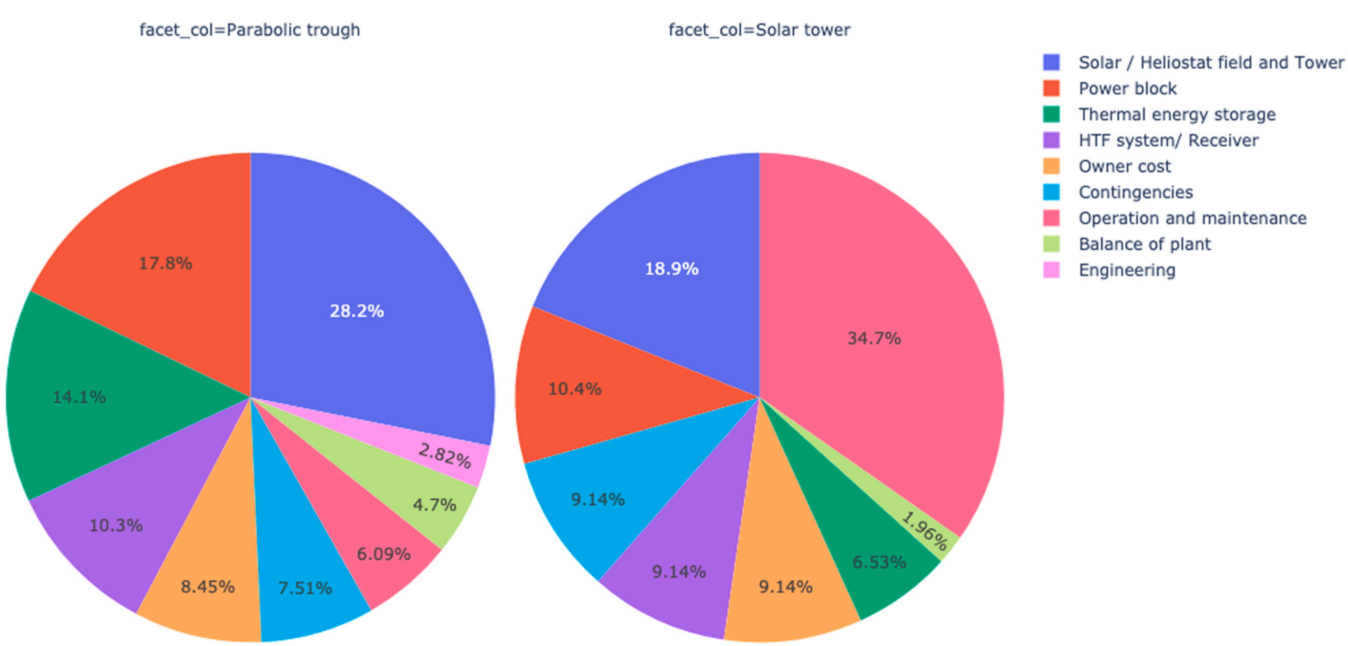

Fig. 7. Share of LCOE of CSP.

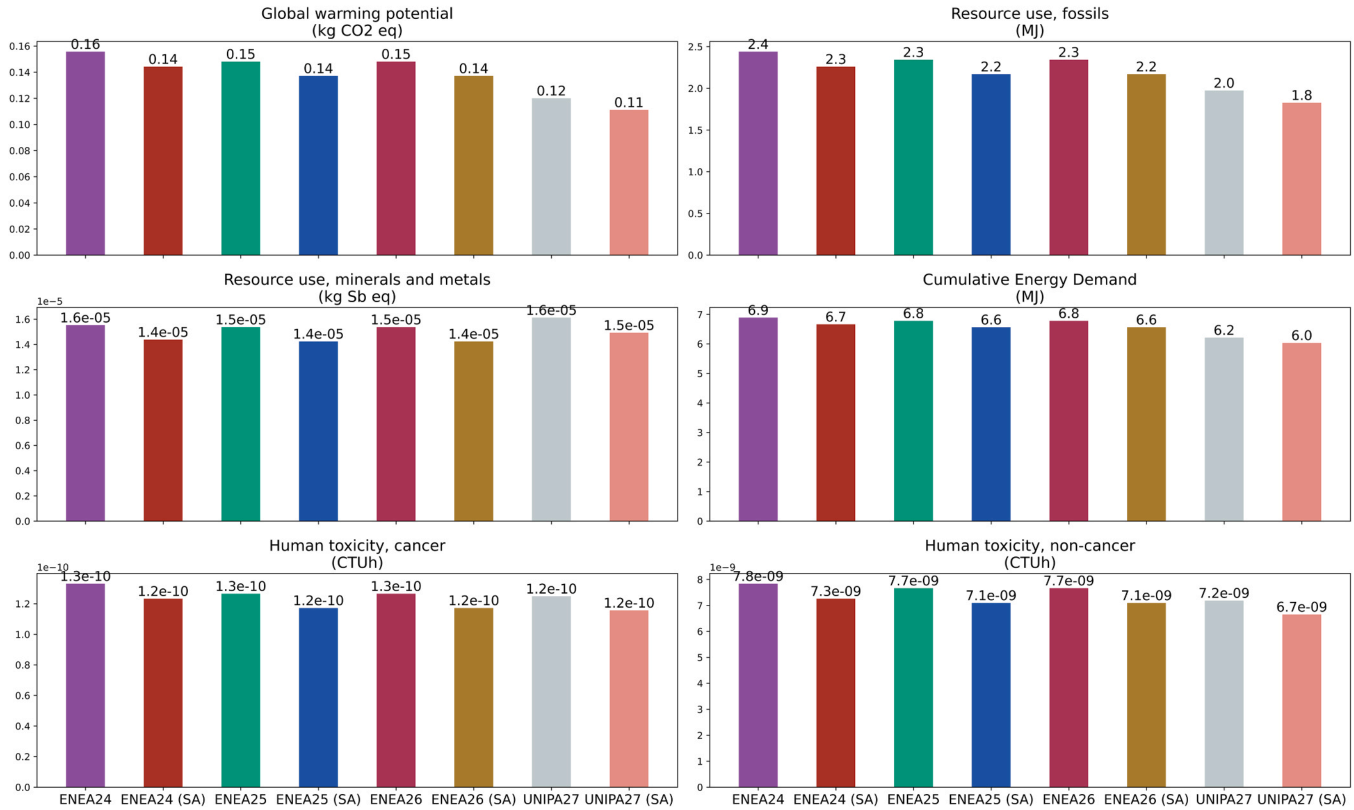

Fig. 8. Life cycle environmental impacts and CED of PSCs in sensitivity analysis (SA).

and CSP, meanwhile there are other solar energy technologies such as solar thermal, solar heating and cooling system, building integrated PV (BIPV) and combination of CSP and PV. The technology development trend tends to combine several solar energy technologies. Among 10 CSP plants under construction, with the total installed capacity of 1.1 GW globally, 7 plants are co-located or hybridized with solar PV, with total hybridizing capacity of PV plants up to 2.6 GW (NREL, 2024). Besides, the application of BIPV is forecasted to be more popular in the future (Tilli and Baggini, 2024), with multiple advantages in generating electricity, thermal insulation and esthetics value. Therefore, the future studies should be focused on such hybrid and trending technologies. At the same time, the future studies should cover both environmental and economic impacts of such systems, compare various technological options and identify the environmental and economic hotspots. This will support the eco-design of the technology, while taking into consideration of financial and cost optimization.

The paper applies LCA for eco-design of solar energy technologies. LCA is a well-developed method, and a popular tool for eco-design, however, the application of LCA requires the specific knowledge on environmental aspects, which is challenging for the engineers, designers and product developers. This leads to the need of an LCA-based eco-design tool, which is simple and easy to use, even for non-professional LCA users. The use of this simplified tool releases the burden during the process of collecting inventory data, selecting life cycle impact method, or calculating the impacts, while estimating and comparing the potential energy demand and environmental impacts of the technologies, and identifying any environmental hotspot during the technologies' life cycle.

Considering that eco-design is applied for technologies at lab scale, it is necessary to upscale the results to pre-industrial or industrial scale. Several studies have been conducted on extrapolating from lab-based data to industrial scale. For an example, Blanco et al. applied probabilistic methods to account for uncertainties in life cycle environmental impacts of multijunction III-IV silicon PV cell (Blanco et al., 2020). In other study, LCA is applied to compare the environmental impacts of scaling up the chemical synthesis of the copper zinc tin sulfide nanoparticle fluid for fabricating thin film PV cells from 20 ml to 100 ml (Jones et al., 2024). This effort should be encouraged and extended to other innovative solar energy technologies such as PSC, OSC and hybrid systems.

For upscaling the technologies from lab-scaled to pre-industrial or industrial manufacture, it will be useful to conduct prospective LCAs to estimate the future environmental impacts of innovative technologies. In prospective LCAs, the hybrid approach of combining lab-scaled data with scenario development, modeling and learning curve extrapolation are commonly applied in the recent years (Erakca et al., 2024). This approach takes the advantages of lab-scaled data of the innovative technologies; however, the obtained results may be uncertain due to the assumptions in scenarios or models. Therefore, sensitivity analysis, uncertainty analysis or probabilistic analysis are encouraged to validate the results and predict the range of the technologies' environmental impacts and costs.

8. Conclusion

The paper applied life cycle approach to support the eco-design of solar energy technologies. The quantifications of life cycle environmental impacts, life cycle costs and LCOEs of PSCs, OSC and CSP indicate that the GWPs of innovative solar cell range from 1.20E-01–3.59E-01 kg CO_2 eq per kWh. The HT-c are between 1.25E-10 and 2.81E-10 CTUh, and the HT-nc are from 7.19E-09–9.13E-09. OSC has the highest environmental impacts for most of the impact categories, except for EP-fw and RU-m. Among the PSCs, ENEA24 has the highest environmental impacts, while UNIPA27 has the lowest environmental impacts. However, the differences in the environmental impacts of the studied PSCs are insignificant.

For CSP, the GWPs are between 7.50E-02 and 8.31E-02 kg CO_2 eq per kWh. The HT-c and HT-nc range from 1.08E-10–1.11E-10 CTUh and between 6.49E-10 and 7.93E-10 CTUh per kWh, respectively. Parabolic trough CSP has higher environmental impacts than solar tower; however, the differences between the two technologies are inconsiderable for most of the impact categories.

The LCOEs of innovative solar PV are from 11.4 EUR to 59.8 EUR per kWh. The LCOEs of PSCs are much higher than that of OSC, while their environmental impacts are generally lower. Compared to the commercial solar PV, the LCOEs of both PSCs and OSC are significantly higher than those of utility-scaled PV system, small PV system with battery, and rooftop PV with battery. The LCOEs of CSP are at 0.58 EUR per kWh for parabolic trough and 0.08 EUR per kWh for solar tower, with the majority of the cost being originated from the collector field.

By analysing the results on life cycle impacts of the technologies, identifying the hotspots during the technologies' life cycle, and comparing them with those of available technologies, the paper suggests several eco-design measures to improve the technologies technically, environmentally and economically. The eco-design of solar PV should firstly focus on the efficiency and lifetime of the cells. Secondly, it is important to consider the material selection, for example material for electrode and absorber layer, as well as fabrication process for depositing the absorber layer, and other layers. Other choice of material to replace gold in electrode includes silver, graphene; and some process such as flash infra annealing, inkjet printing, sintering screen print may be considered.

For the innovative PSC of the NEST project, the eco-design should consider several material options such as MgF_2 for interlayer, SnO_2 doped Ru for ETL, $MAPbI_3$ for absorber and MoO_3 for HTL. More importantly, the combination of various materials for different layers should be taken into accounted. For an example, the combination of SnO_2 doped Ru, $MAPbI_3$ and MoO_3, and SnO_2, CsFAMA and MoO_3 are better than SnO_2, $MAPbI_3$ and a-Si:H.

For CSP, the eco-design should focus on reducing the impacts from co-generation of electricity from natural gas. This can be done through using low-impact fuels for co-generation such as bio-based fuels. In other cases, the impacts from co-generation in CSP power plant can be avoid by combining CSP system with PVs or hydrogen. The most impactful 'solar-to-power' components should be taken into account, such as collector field for most of the impacts, HTF and power generation unit for minimizing acidification, eutrophication, ecotoxicity and metal and mineral use.

Last but not least, other life cycle stages such as transportation, consumption and end-of-life, though contribute small shares of the total impact, need to be taken into account for the best and combined effect of the eco-design measures. These measures not only reduce the environmental impacts but also reduce the cost of electricity generated by these innovative technologies, to bring them closer to the market readiness level.

CRediT authorship contribution statement

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

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.

Acknowledgments

This work has been funded by the European Union – NextGenerationEU, Mission 4, Component 2, Project NEST, CUP B73C22001280006, Spoke 1.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2025.108961.

Data availability

Data will be made available on request.

References

Alberola-Borràs, J.-A., Baker, J.A., De Rossi, F., Vidal, R., Beynon, D., Hooper, K.E.A., Watson, T.M., Mora-Seró, I., 2018a. Perovskite photovoltaic modules: life cycle assessment of pre-industrial production process. iScience 9, 542–551. https://doi.org/10.1016/j.isci.2018.10.020.

Alberola-Borràs, J.-A., Vidal, R., Juárez-Pérez, E.J., Mas-Marzá, E., Guerrero, A., Mora-Seró, I., 2018b. Relative impacts of methylammonium lead triiodide perovskite solar cells based on life cycle assessment. Sol. Energy Mater. Sol. Cells 179, 169–177. https://doi.org/10.1016/j.solmat.2017.11.008.

Albertí, J., Raigosa, J., Raugei, M., Assiego, R., Ribas-Tur, J., Garrido-Soriano, N., Zhang, L., Song, G., Hernández, P., Fullana-i-Palmer, P., 2019. Life cycle assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels. Sustain. Cities Soc. 47, 101467. https://doi.org/10.1016/j.scs.2019.101467.

Anctil, A., Lee, E., Lunt, R.R., 2020. Net energy and cost benefit of transparent organic solar cells in building-integrated applications. Appl. Energy 261, 114429. https://doi.org/10.1016/j.apenergy.2019.114429.

Bahlawan, H., Morini, M., Pinelli, M., Poganietz, W.-R., Spina, P.R., Venturini, M., 2019. Optimal design of a hybrid energy plant by accounting for the cumulative energy demand. Energy Procedia 158, 2834–2840. https://doi.org/10.1016/j.egypro.2019.02.046.

Blanco, C.F., Cucurachi, S., Dimroth, F., Guinée, J.B., Peijnenburg, W.J.G.M., Vijver, M. G., 2020. Environmental impacts of III–V/silicon photovoltaics: life cycle assessment and guidance for sustainable manufacturing. Energy Environ. Sci. 13, 4280–4290. https://doi.org/10.1039/D0EE01039A.

Burkhardt, J.J., Heath, G.A., Turchi, C.S., 2011. Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives. Environ. Sci. Technol. 45, 2457–2464. https://doi.org/10.1021/es1033266.

Corona, B., Miguel, G.S., Cerrajero, E., 2014. Life cycle assessment of concentrated solar power (CSP) and the influence of hybridising with natural gas. Int. J. Life Cycle Assess. 19, 1264–1275. https://doi.org/10.1007/s11367-014-0728-z.

Corona, B., Ruiz, D., San Miguel, G., 2016. Life cycle assessment of a HYSOL concentrated solar power plant: analyzing the effect of geographic location. Energies 9, 413. https://doi.org/10.3390/en9060413.

Dahmani, N., Belhadi, A., Benhida, K., Elfezazi, S., Touriki, F.E., Azougagh, Y., 2022. Integrating lean design and eco-design to improve product design: from literature review to an operational framework. Energy Environ. 33, 189–219. https://doi.org/10.1177/0958305X21993481.

Damiani, M., Ferrara, N., Ardente, F., 2022. Understanding Product Environmental Footprint and Organisation Environmental Footprint methods. Publications Office of the European Union, Luxembourg.

Dumortier, M., Haussener, S., 2015. Design guidelines for concentrated photo-electrochemical water splitting devices based on energy and greenhouse gas yield ratios. Energy Environ. Sci. 8, 3069–3082. https://doi.org/10.1039/C5EE01269D.

EC, 2021. Understanding product environmental footprint and organisation environmental footprint methods [WWW Document]. URL ⟨https://circabc.europa.eu/ui/group/6e9b7f79-da96-4a53-956f-e8f62c9d7fed/library/537534a4-9c76-40a1-b488-e9127db2befd/details?download=true⟩.

Ecoinvent, 2020. Ecoinvent database version 3.7 [WWW Document]. URL ⟨https://ecoinvent.org/the-ecoinvent-database/⟩.

Erakca, M., Baumann, M., Helbig, C., Weil, M., 2024. Systematic review of scale-up methods for prospective life cycle assessment of emerging technologies. J. Clean. Prod. 451, 142161. https://doi.org/10.1016/j.jclepro.2024.142161.

EPLCA, 2018. Environmental footprint (EF) impact assessment [WWW Document]. URL ⟨https://eplca.jrc.ec.europa.eu/EFVersioning.html⟩.

Frischknecht, R., Itten, R., Sinha, P., De Wild-Scholten, M., Zhang, J., Heath, G.A., Olson, C., 2020. Life cycle inventories and life cycle assessments of photovoltaic systems (No. NREL/TP-6A20-73853, 1561526). https://doi.org/10.2172/1561526.

Gobio-Thomas, L.B., Darwish, M., Stojceska, V., 2023. Environmental impacts of solar thermal power plants used in industrial supply chains. Therm. Sci. Eng. Prog. 38, 101670. https://doi.org/10.1016/j.tsep.2023.101670.

IEA, 2021. Net zero by 2050 a roadmap for the global energy sector. International Energy Agency. ⟨https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf⟩ (URL).
IEA, 2022a. Greenhouse gas emissions from energy data explorer. URL: ⟨https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview/emissions-by-sector#abstract⟩.
IEA, 2022b. The role of critical minerals in clean energy transitions. URL: ⟨https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf⟩.
IRENA, 2019. Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-economic aspects (A Global Energy Transformation: paper). International Renewable Energy Agency, Abu Dhabi.
IRENA, 2024. Renewable Power Generation Costs in 2023. International Renewable Energy Agency, Abu Dhabi.
ISO, 2006a. ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework.
ISO, 2006b. ISO 14044:2006, Environmental management - Life cycle assessment - Requirements and guidelines.
Jones, M.D.K., Willis, B.L., Campbell, S., Kartopu, G., Maiello, P., Punathil, P., Cheung, W.M., Woolley, E., Jones, L.C.R., Oklobia, O., Holland, A., Barrioz, V., Zoppi, G., Beattie, N.S., Qu, Y., 2024. Ecodesign of kesterite nanoparticles for thin film photovoltaics at laboratory scale. ACS Sustain. Chem. Eng. 12, 11613–11627. https://doi.org/10.1021/acssuschemeng.4c02841.
Khan, A.A., Molina, P., Reichel, C., Protti, A.A., Neuhaus, D.H., Rentsch, J., Nold, S., 2024. The European union's ecodesign directive – analysis of carbon footprint assessment methodology and implications for photovoltaic module manufacturers. Sol. RRL 8, 2301011. https://doi.org/10.1002/solr.202301011.
Kost, C., Muller, P., Schweiger, J.S., Fluri, V., Thomsen, J., 2024. Levelized Cost of Electricity- Renewable Energy Technologies. Fraunhofer Institute for Solar Energy Systems, ISE.
Li, Q., Monticelli, C., Zanelli, A., 2022. Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. Renew. Energy 195, 906–917. https://doi.org/10.1016/j.renene.2022.06.075.
Luu, L.Q., Cellura, M., Longo, S., Guarino, F., 2024. A comparison of the life-cycle impacts of the concentrating solar power with the product environmental footprint and ReCiPe methods. Energies 17, 4461. https://doi.org/10.3390/en17174461.
Montana, F., Cellura, M., Di Silvestre, M.L., Longo, S., Luu, L.Q., Riva Sanseverino, E., Sciumè, G., 2024. Assessing critical raw materials and their supply risk in energy technologies—a literature review. Energies 18, 86. https://doi.org/10.3390/en18010086.
Nkinyam, C.M., Ujah, C.O., Nnakwo, K.C., Kallon, D.V.V., 2025. Insight into organic photovoltaic cell: prospect and challenges. Unconv. Resour. 5, 100121. https://doi.org/10.1016/j.uncres.2024.100121.
NREL, 2021. To toss, repair, or recycle? how human behavior affects the fate of aging solar panels. URL: ⟨https://www.nrel.gov/news/detail/program/2021/to-toss-repair-or-recycle-how-human-behavior-affects-the-fate-of-aging-solar-panels⟩.
NREL, 2024. SolarPACES - concentrating solar power (CSP) projects. URL: ⟨https://solarpaces.nrel.gov/by-technology⟩.
NREL, 2025. Best research-cell efficiency chart. URL: ⟨https://www.nrel.gov/pv/cell-efficiency⟩.
Ogletree, A., 2025. How much do solar panels cost in 2025? Forbes. URL: ⟨https://www.forbes.com/home-improvement/solar/cost-of-solar-panels/⟩.
Olmedo-Torre, N., Canals Casals, L., Amante García, B., 2018. Sustainable design of a thermosolar electricity generation power plant in Burkina Faso. J. Environ. Manag. 226, 428–436. https://doi.org/10.1016/j.jenvman.2018.08.043.
Pelay, U., Azzaro-Pantel, C., Fan, Y., Luo, L., 2020. Life cycle assessment of thermochemical energy storage integration concepts for a concentrating solar power plant. Environ. Prog. Sustain. Energy 39, e13388. https://doi.org/10.1002/ep.13388.
Ratner, S., Gomonov, K., Revinova, S., Lazanyuk, I., 2020. Eco-design of energy production systems: the problem of renewable energy capacity recycling. Appl. Sci. 10, 4339. https://doi.org/10.3390/app10124339.
Raugei, M., Frischknecht, R., Olson, C., Sinha, P., Heath, G., 2016. Methodological Guidelines on Net Energy Analysis of Photovoltaic Electricity (No. IEA-PVPS Task 12. Report T1207: 2016). International Energy Agency.
Rebitzer, G., Nakamura, S., 2007. Chapter 3. Environmental life cycle costing. Environmental Life Cycle Costing. CRC Press, pp. 35–58.
Rossi, M., Germani, M., Zamagni, A., 2016. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J. Clean. Prod. 129, 361–373. https://doi.org/10.1016/j.jclepro.2016.04.051.
Rossi, F., Heleno, M., Basosi, R., Sinicropi, A., 2020. Environmental and economic optima of solar home systems design: a combined LCA and LCC approach. Sci. Total Environ. 744, 140569. https://doi.org/10.1016/j.scitotenv.2020.140569.
San Miguel, G., Corona, B., 2014. Hybridizing concentrated solar power (CSP) with biogas and biomethane as an alternative to natural gas: analysis of environmental performance using LCA. Renew. Energy 66, 580–587. https://doi.org/10.1016/j.renene.2013.12.023.
Sánchez, S., Vallés-Pelarda, M., Alberola-Borràs, J.-A., Vidal, R., Jerónimo-Rendón, J.J., Saliba, M., Boix, P.P., Mora-Seró, I., 2019. Flash infrared annealing as a cost-effective and low environmental impact processing method for planar perovskite solar cells. Mater. Today 31, 39–46. https://doi.org/10.1016/j.mattod.2019.04.021.
Scharber, M.C., Sariciftci, N.S., 2013. Efficiency of bulk-heterojunction organic solar cells. Prog. Polym. Sci. 38, 1929–1940. https://doi.org/10.1016/j.progpolymsci.2013.05.001.
Steffen, B., Beuse, M., Tautorat, P., Schmidt, T.S., 2020. Experience curves for operations and maintenance costs of renewable energy technologies. Joule 4, 359–375. https://doi.org/10.1016/j.joule.2019.11.012.
Tian, X., Stranks, S.D., You, F., 2020. Life cycle energy use and environmental implications of high-performance perovskite tandem solar cells. Sci. Adv. 6. https://doi.org/10.1126/sciadv.abb0055.
Tilli, F., Baggini, A., 2024. Analysis of the technological innovation system for BIPV in Italy. IEA Photovolt. Power Syst. Program. (PVPS). https://doi.org/10.69766/ISPE8690.
Tsang, M.P., Sonnemann, G.W., Bassani, D.M., 2016. Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. Sol. Energy Mater. Sol. Cells 156, 37–48. https://doi.org/10.1016/j.solmat.2016.04.024.
UNEP, 2021. Term Eco-design. URL: ⟨https://www.eea.europa.eu/help/glossary/eea-glossary/eco-design#:~:text=Eco%2Ddesign%20considers%20environmental%20aspects,throughout%20the%20product%20life%20cycle⟩.
Whitaker, M.B., Heath, G.A., Burkhardt, J.J., Turchi, C.S., 2013. Life cycle assessment of a power tower concentrating solar plant and the impacts of key design alternatives. Environ. Sci. Technol. 47, 5896–5903. https://doi.org/10.1021/es400821x.
Zhang, J., Gao, X., Deng, Y., Li, B., Yuan, C., 2015. Life cycle assessment of titania perovskite solar cell technology for sustainable design and manufacturing. ChemSusChem 8, 3882–3891. https://doi.org/10.1002/cssc.201500848.
Zhang, J., Gao, X., Deng, Y., Zha, Y., Yuan, C., 2017. Comparison of life cycle environmental impacts of different perovskite solar cell systems. Sol. Energy Mater. Sol. Cells 166, 9–17. https://doi.org/10.1016/j.solmat.2017.03.008.