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Review article

A conceptual framework to guide the eco-design of solar energy technologies

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ABSTRACT

Solar energy will make a significant contribution to the global energy supply in the near future as well as in the long-term, which suggests the introduction of innovative technologies. Eco-design is encouraged to be applied at the early stage of technology development so that these innovative solar energy technologies could be developed with the largest energy and environmental benefits. The paper presents a conceptual framework, which integrates general guidelines and life cycle assessment to advise the eco-design of solar energy technologies. The framework includes a list of 164 eco-design guidelines for solar photovoltaics and concentrating solar power technologies, being compiled from the existing literature, covering all life cycle stages, and sub-components constituting the technologies. Apart from the general guidelines, the framework proposes the integration of life cycle assessment to obtain specific eco-design measures for a particular solar energy technology. The majority of guidelines/ measures are relevant to 'R' measures such as refuse, rethink, reduce, reuse, repair, refurbish, remanufacturing, recycle and recover of materials, energy, components, products and technologies. This framework should be applied as a quick review tool for the eco-design solar energy technologies taking into account environmental aspects over their life cycle. For a specific technology, a life cycle assessment-based guideline is recommended to identify the most suitable and context-sensitive measures.

1. Introduction

Solar energy is expected to contribute 14 TW, accounting for 20% of global energy supply and 23% of the electricity and heat supply by 2050 (IEA, 2021). This is a substantial increase within 30 years, from 700 GW of solar photovoltaics (PV) installed capacity in 2020 (IRENA, 2024). The increase of solar energy deployment means that there will be more innovative solar technology being studied and developed. These technologies not only reduce the greenhouse gas (GHG) emissions of energy sectors to decarbonize the economy but also are expected to bring out other environmental impacts and/ or benefits.

It is estimated that 80% of the technologies' environmental impacts is determined in the design phase (Pollini and Rognoli, 2021; Zhang et al., 2015). The choice of material is also crucial for the product ecological footprint because it interferes not only with the impacts of one main material itself but the combined effects of several materials over the product life cycle. Eco-design integrates the environmental aspects into the product development process by balancing ecological and economic requirements. It considers environmental aspects at all stages of the product development process, striving for products which make the lowest environmental impacts throughout the product life cycle, while maintaining the products' quality level according to its ideal usage. Therefore, guidelines for 'ecologically' designing solar energy technologies, considering their importance in decarbonizing the energy system, their impacts and benefits on material and natural resource depletion are essential to further development of solar energy technologies.

In the literature, there are several eco-design guidelines, which are applicable either for all kinds of product or for a specific sector, have been proposed, being summarized in Table 1. For example, Vilochani et al. reviewed the sustainable product development (SDP) practice and consolidated into 61 SDP practice (Vilochani et al., 2024). These SDP practices are classified according to three criteria: context of application (seven stages of product development process planning, conceptual design, detail design, testing and prototype, production and market

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Nomenclature

ADP_f	Abiotic Depletion Potential, fossil
BIPV	Building Integrated PV
CED	Cumulative energy demand
DfAD	Design for Adaptability and Disassembly
EC	European Commission
EPBT	Energy Payback Time
EROI	Energy Return On Investment
GHG	Greenhouse Gas
GW	Gigawatt
IEA	International Energy Agency
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MJ	Megajoule
NER	Net Energy Ratio
PEFCR	Product Environmental Footprint Category Rule
PV	Photovoltaics
SDP	Sustainable Product Development
TW	Terawatt

Table 1
Literature review of guidelines with sustainability concepts.

Author	Guideline	Characteristics
(Vilochani et al., 2024)	Sustainable Product Development Practice	Including three pillars of sustainability
(Pollini and Rognoli, 2021)	Design for sustainability (D4S)	Material implication of the guidelines
(Apel et al., 2024)	Eco-design guideline	Covering three pillars of sustainability Focusing on chemical and materials
(Campos-Carriedo et al., 2024)	Sustainable by design	Covering three pillars of sustainability Applying for hydrogen production technologies
(Munaro et al., 2022)	• Design for Adaptability and Disassembly • Design for Deconstruction or Design for Disassembly	Suggesting on measures regarding the end-of-life of building

launch, product review and gate assessment and four support process strategic planning, programme management, portfolio management, technology development based on ISO/TR 14062:2002 describes concepts and current practices relating to the integration of environmental aspects into product design and development). The authors pointed out that most of the pre-consolidated practices predominantly address the environmental pillar while social and economic pillars are still lagging.

Pollini and Rognoli (Pollini and Rognoli, 2021) analysed the eco-design guidelines and material implication of Brexet and Van Hemel 1997. These 29 guidelines considered six aspects of new concept development, material selection, optimization of production technique, optimization of distribution system, impact reduction during the use stage, and optimization of initial lifetime and the end of life. These guidelines only focused on two main areas of materials and energy consumption.

In specific sectors, there are several studies related to eco-design of product. Apel et al. (Apel et al., 2024) reviewed five approaches of Joint Research Centre of European Commission (EC), European Environment Agency, Organisation for Economic Co-operation and Development, Cefic and ChemSec for safe and sustainable design of chemicals and materials. These studies resulted a framework with clear definition and procedure (or workflow, approach) for sustainable design of chemical and materials. However, no eco-design guideline has been provided. In the energy sector, Campos-Carriedo et al. (Campos-Carriedo et al., 2024) applied the principles of EcoReport tool to promote the sustainable design in hydrogen production, considering several sustainability indicators of energy efficiency (environment), manufacturing cost (economy), child labour, contribution to economic development, fair salary, frequency of force labour, gender wage gap and health expenditure (society). In building sector, Munaro et al. (Munaro et al., 2022) identified that there is a lack of understanding about the eco-design concepts in the building sector, which needs more information on eco-design methods, deconstruction strategies, reusing of materials and life cycle tools to support for decision making process for sustainable building. Currently, the most inclusive and sustainable eco-design method for building deconstruction is Design for Adaptability and Disassembly (DfAD). The authors proposed an integrated methodology based on DfAD.

Although there are available eco-design guidelines for various products, limited focus has been tributed to the development of guidelines for solar energy technologies, especially those can be applicable in emerging, innovative solar energy technologies. Besides, most of the papers which relate to the eco-design of solar energy technologies, concentrate on the technical performance, without considering the environmental aspect thoroughly, for examples lead-free perovskite solar cells (Baro and Borgohain, 2026), nanofluid (Sheikholeslami and Khalili, 2024) and bi-fluid of air and refrigerant (Aktekeli et al., 2025) used in solar PV thermal systems. This gap induces the need for developing a framework to guide the eco-design of solar energy technologies.

Moreover, the current literature proposed a list of eco-design guidelines, but they do not support the practical application of the guidelines, i.e without clarifying when and how the guidelines should be applied and by whom. Therefore, this paper aims to provide a conceptual framework to guide the eco-design solar energy technologies, which includes three pieces of information that are crucial for the application and usage of the guideline in the practice: who use, when to use and involvement/ effort needed for implementing these guidelines.

Finally, the existing guidelines provide the general directions to design the product towards environmental sustainability; however, they fail to suggest the specific information on the materials, components, fabrication process or life cycle stages to improve a particular solar energy technology. Consequently, the framework integrates the guidelines with life cycle assessment (LCA) for clear and actionable measures for the eco-design of particular solar energy technologies.

The paper is structured into four main sections, starting with introduction of the context and identification of the research gap, followed by a section describing the method and data used in the study. The core of the paper lies in the Result and Discussion section which presents the conceptual framework to guide the eco-design of solar energy technologies, which include general eco-design guidelines, specific eco-design measures from LCA, energy indicators, and other LCA methodological recommendations. There are two illustrative examples of applying the conceptual framework and some discussions on strengths, limitations and implications of the conceptual framework. The paper ends with a concluding section and some suggestions on research and development works for sustainable future of solar energy technologies.

2. Materials and methods

The proposed eco-design guidelines on solar energy technologies starts from a large collection of general guidelines in the literature. These literature-based guidelines are presented in the forms of examples or suggestions. They are then analysed and classified by their goals indicating the present situation and how to change the present situation (Russo et al., 2017). The main goals can be divided into sub-goals which are the life cycle stages and sub-components they are aiming at. From these sub-goals, there are suggestions on how to manipulate the present situation for achieving the goal and sub-goals. Suggestions should be practical and operationally feasible, with adequate tools and knowledge of specific situation. Besides, the guidelines present some examples of possible solutions and applications of guidelines. Finally, several information is added to cover the research gaps, including the involvement and effort needed when implementing these guidelines, who use the guidelines and when they should be applied. The steps of developing these proposed eco-design guidelines on solar energy technologies are presented in Fig. 1 and further explained below.

2.1. Step 1: Collect all existing eco-design guidelines

The search for existing eco-design guidelines was conducted on Scopus with searching key words of "eco-design AND solar energy technology" within titles, abstract and keywords. When the results are limited to 'eco-design', using the 'advanced search' function of Scopus (the publication must contain the keyword 'eco-design'), 62 publications were obtained. The abstracts of these publications are read, and their research topics are identified. In general, these publications have three patterns:

a) Several publications applied LCA or revised (and improved) the LCA approach by combining it with other tools (or concepts) to support eco-design of a specific energy technology. For an example, LCA is integrated with perception of workers of the hidden injustice of solar supply chain (Sovacool and Stock, 2024). Siwiec and Pacana (Siwiec and Pacana, 2024) combined LCA and customer satisfaction using entropy for eco-design of solar PV. Riondet matched the life cycle approach with different aspects of upscaling technologies for environmental assessment and eco-design (Riondet et al., 2023). A method of combining mixed integer linear programming with LCA and LCC for comparing environemtnal and economic optimal design of battery-integrated solar PV home system in (Rossi et al., 2020).
b) These LCA-based eco-design publications not only cover solar energy technologies (13 papers) but also extend to other technologies of renewable energy (9 papers), for example wind energy, hydrogen, green energy supply chain and energy efficiency of household appliances.
c) Several publications provided qualitative and analytical eco-design guides (16 papers), for example integrating circular economy into the design of all kinds of product (Kamp Albæk et al., 2020) and of solar thermal system (Milousi and Souliotis, 2023). Ratner et al. developed eco-design guidelines for recycling of solar PV and wind tourbine (Ratner et al., 2020). Yang and Vezzoli (Yang and Vezzoli, 2024) aimed at eco-design guideline for furniture. Martínez Leal et al (Martínez Leal et al., 2020). provided guidelines on design for (and from) recycling and a circular product design guideline was proposed by (Kamp Albæk et al., 2020). These eco-design guidelines can be applied to one technology or are applicable for all technologies (10 papers).

The study proposes a conceptual framework that includes both general eco-design guidelines and LCA based eco-design measures for solar energy technologies; therefore, in the first screening, the selected papers include 13 LCA-based eco-design publications covering solar energy technologies in point (b) and 16 general eco-design publications being applicable for all kinds of products in point (c), at a total of 29 papers. Among 13 publications in point (b), 9 publications provided specific examples of measures for eco-designing various solar energy technologies, which are cited in 3.3. Of all 16 papers in point (c), 13 publications that can be extracted information being suitable for the eco-design of solar energy technologies, which are analyzed in 3.2 and cited in the list of guidelines in the supporting information SI1. Consequently, the final screening results in a total of 22 papers with eco-design guidelines and measures which are applicable for solar energy technologies.

2.2. Step 2: Extracting and analyzing the information

The eco-design guidelines of 13 publications in point (c) are extracted and analysed for following aspects:

•The existing guidelines being selected from the literature were analysed. First, identify the verbs and the subject used in each guideline, for example in the guideline 'Make it easy to clean the product and components', the verb phases of 'make it easy' and 'clean' are identified, the nouns/ subjects of 'product' and 'components' are identified. Another example in the guideline 'Facilitate collection and transportation for disposed furniture, the verb 'facilitate' is identified, and the nouns of 'collection', 'transportation' and 'disposed furniture' is identified. In general, the verbs are related to the eco-design action,

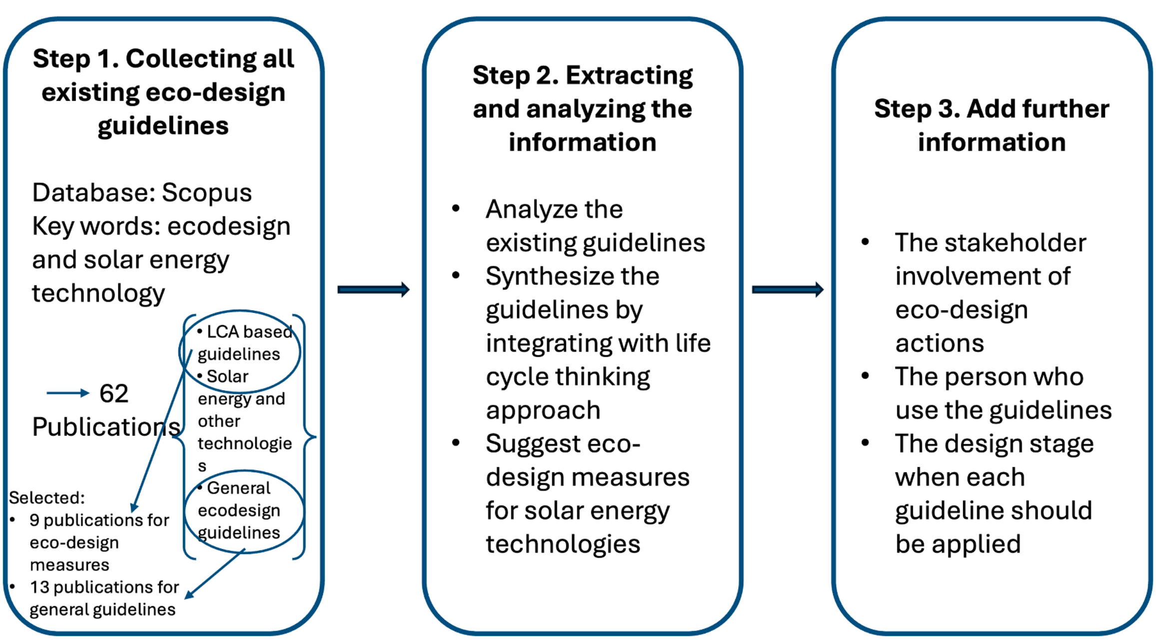

Fig. 1. Step for developing the eco-design guidelines for solar energy technologies.

while the nouns and subjects are related to the life cycle stages and the sub-components of the life cycle stages. Then, group the similar verb and subject together, for example ‘make it easy’ is similar to ‘facilitate’, ‘manufacture’ is similar to ‘production’.

•Synthesize the guidelines by matching it with life cycle thinking approach. This is done by classifying the guidelines by life cycle stage of the actions, and sub-components of the life cycle stages, for example production stage includes manufacturing of products, selecting materials, packaging, etc. This is the most important point because it will match the eco-design guidelines with the specific results obtained by LCA. Besides, the eco-design guidelines are categorized by design stages and users of the guidelines, to support the easy use and practical applications of the guidelines. These two rules of categorization will be further explained in point 2 and 3 of the next section, 2.3. Step 3: Add further information.

•Suggest specific examples of eco-design measures for solar energy technologies. This is done by extracting the information from LCA-based eco-design guidelines in the p publications in point (b).

2.3. Step 3: Add further information

Several information was added to support the application/ usage of the eco-design guidelines in the practice, including:

•List of stakeholders of interest for potential co-creation. The stakeholders include both the staffs of company and external ones to cover the whole supply chain of solar energy technologies. For the success of eco-design process, both company and suppliers, users should be involved and co-implementing eco-design measures. The list of interested stakeholders is developed by matching the eco-design suggestions to the life cycle stages and the key stakeholders of each stage.

•List of target audience of the guidelines. The audience of the guidelines are internal staffs of the company, who use the eco-design guidelines, for example business managers, engineer, environmental analysist, designers. The list of target audience is done by matching the eco-design suggestions to the production stage and the person who involves the design, development, manufacture and marketing and sale of the product.

•Stage of innovation development to apply the eco-design guidelines, for example at conceptual design stage, at design finalization stage. This is done by matching the eco-design suggestions to the innovation development pathway.

3. Results and discussion

3.1. Conceptual framework to guide the eco-design of solar energy technologies

Fig. 2 presents the conceptual framework to guide the eco-design of solar energy technologies by integrating LCA with general eco-design guidelines. The general eco-design guidelines and LCA share the same principle of life cycle thinking and covering all life cycle stages of the product system. While these general eco-design guidelines are applicable for all solar energy technologies, the LCA quantifies the life cycle environmental impacts of a particular product.

The framework starts with an identification of the specific solar energy product, with clear system boundary, e.g. life cycle stages covered within that boundary, and users of the framework. Then the general guidelines should be applied to review all the exiting actions that can be implemented in solar energy sector. The general guidelines will clearly be described in the next section (3.2). The concerning life cycle stages and involved stakeholders are also clearly mentioned in 3.2.

Because the general guidelines do not provide the recommendations for a particular solar energy product, especially innovative technologies for examples tandem PV cells based on perovskite and silicon. It is recommended that life cycle approach should be applied to quantify the environmental impacts of the technology covering their whole life cycle and identify the environmental hotspot for focusing the effort. An LCA will provide the specific results based on context e.g. a particular technology, its technical characteristics, their location, construction, installation, and usage. The guidelines based on LCA, with focus on the ‘energy’ indicator will be provided in 3.3.

Several LCAs may be conducted to compare different choice of materials, components, transportation options, or end-of-life treatment strategies. Besides, scenario development and hotspot identification would further refine the eco-design measures, by concentrating the effort into the most impactful stage (or component). Depending on the available resources, especially the expertise, either simple LCA or comprehensive LCA may be performed. Other information to support the implementation of LCA in this conceptual framework such as some simple LCA tools and methodological choice for comprehensive LCA are

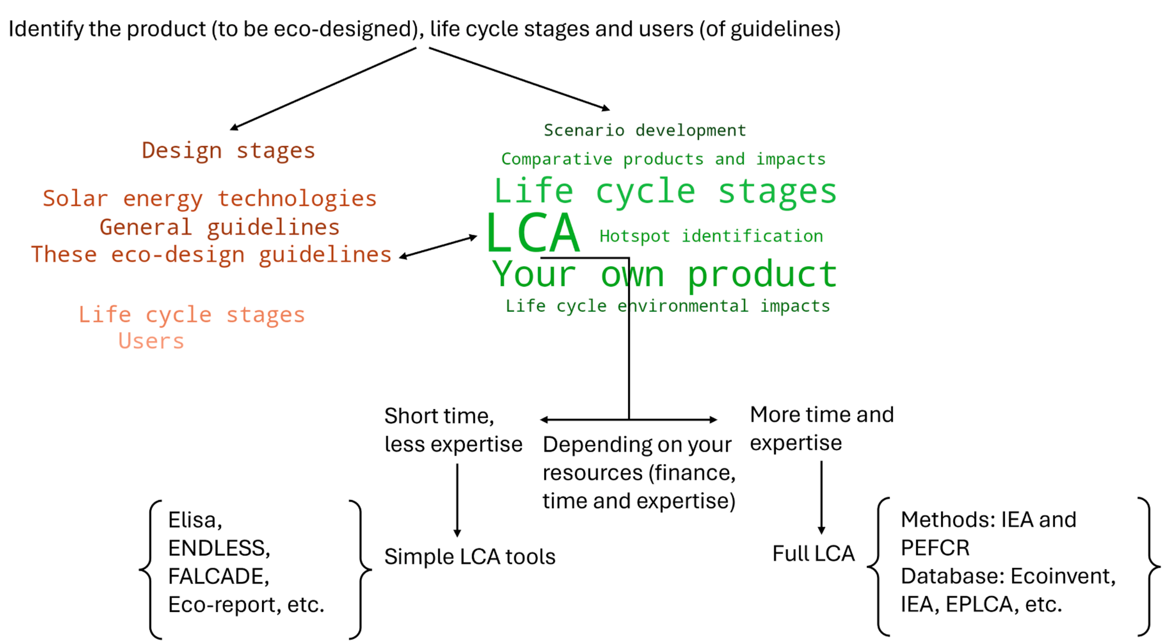

Fig. 2. Integrating LCA into the general eco-design guidelines.

suggested in 3.3.

In case that the LCA is too complex for designers to apply to their product, some simple LCA tools are recommended. For solar heating and cooling systems, (Longo et al., 2020) proposed Elisa, an excel-based tool for researchers, designers and decision makers to estimate the life cycle energy and environmental benefits and/or impacts of thermal solar heating and cooling system, conventional system and PV assisted system. This tool can be used to select the best technological option considering the life cycle energy from the environmental point of view at the first stage of eco-design process. Other LCA- relevant tools that support the eco-design include ENDLESS (Ardente et al., 2003), FALCADE (Ardente et al., 2004) and Eco-report (European Commission. Joint Research Centre, 2024). ENDLESS and FALCADE include environmental, energy and economic indicators, and can be applied for any products, while Eco-report is specifically designed for energy related products. Besides, ENDLESS and Eco-report aim at the recycling of product, e.g. end of life stage, while FALCADE covers the whole life cycle of the product.

3.2. General eco-design guidelines

The general guidelines proposed in this paper include 164 guidelines, covering five life cycle stages: extraction, production, transportation, use and end of life. Three quarters of the guidelines concern several life cycle stages simultaneously, for examples 'Extraction and Production', 'Production, Use, and End of life', or even cover all life cycle stages of the product. Besides, apart from the product itself, the guidelines cover six sub-components to substitute product and manufacturing process, including Auxiliary, Energy, Material, Packaging, Process, and Waste which are categorized based on different. The sub-component 'Information' is relevant to sharing or providing information to the users or updating information of producers. Fig. 3 presents the link of eco-design guidelines with life cycle stages and sub-components.

Regarding the life cycle stages, the majority of guidelines are relevant to end-of-life stage (107 guidelines), production stage (79 guidelines) and use stage (75 guidelines). Among 107 guidelines concerning the end-of-life stage and other stages, only seven guidelines are related to waste treatment, which are categorized into sub-component of 'Waste'. In such cases, eco-design during end-of-life stage aims at preventing waste generation, rather than waste treatment.

There are 12 guidelines out of 79 guidelines which are implemented during the production stage only. These guidelines have three patterns: (1) they aim at increasing the efficiency or productivity of the manufacturing process, for example optimize the production chain, apply clean production process, reduce the number of production steps, etc (sub-component 'Process'); (2) they improve the product quality for manufacturer's competitiveness or marketing/ sale, for example, identifying or improving the product competitiveness by applying eco-design measures (sub-component 'Product'); (3) they relate to building the internal knowledge of the manufacturer (sub-component 'Information'), for example investigate the traditional products' characteristics and reproduce them in new solutions to increase the perception of familiarity.

20 guidelines on use stage solely are diverse and cover some actions: to increase energy efficiency of the product, use durable packing, avoid waste of energy and consumables, and improve the product efficiency, aesthetics, function and quality. The detailed analysis of all eco-design guidelines presented in the supporting information SI2.

Stakeholder involvement within the eco-design process

One of the main drivers for the continuous implementation of eco-design is the requirement from stakeholders and customers. Customer demand is the main driver for eco-design. Therefore customers (or users) are crucial players of the eco-design process. At the same time, the eco-design process is deployed at the production facility, which requires the participation of the company itself, as well as concerns the suppliers of intermediates, and service providers. In other words, it is essential to attract the involvement of various stakeholders covering both upstream and downstream processes of the whole supply chain.

The eco-design process requires the involvement of four key stakeholders, including the company, the upstream suppliers (such as material and energy suppliers), the downstream suppliers (such as waste treatment and logistics service providers), and the users. In this study, the responsibilities of implementing eco-design actions are shared among these stakeholders: (1) sole responsibility of the company, (2) shared responsibility between the company and the users, (3) shared responsibility between the company and the suppliers and (4) shared responsibility among the company, the users, and the suppliers. Fig. 4 presents the stakeholder involvement of eco-design process.

Actions belong to the sole responsibility of the company are related to the product. Besides, the company has shared responsibility with suppliers regarding the auxiliary, energy, material, and transport. An example of contribution of suppliers to the eco-design of solar energy technologies is to provide the biodegradable, renewable, (socially) responsible and sustainable materials. The company, through the investigation and selection of the most appropriate and sustainable material, can improve the environmental profiles of the technologies. In

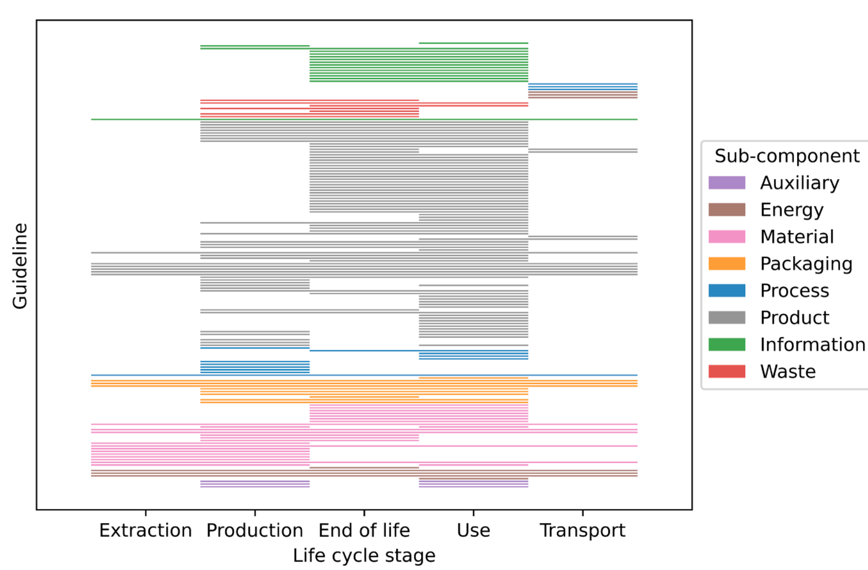

Fig. 3. Links among eco-design guidelines with life cycle stages and sub-components.

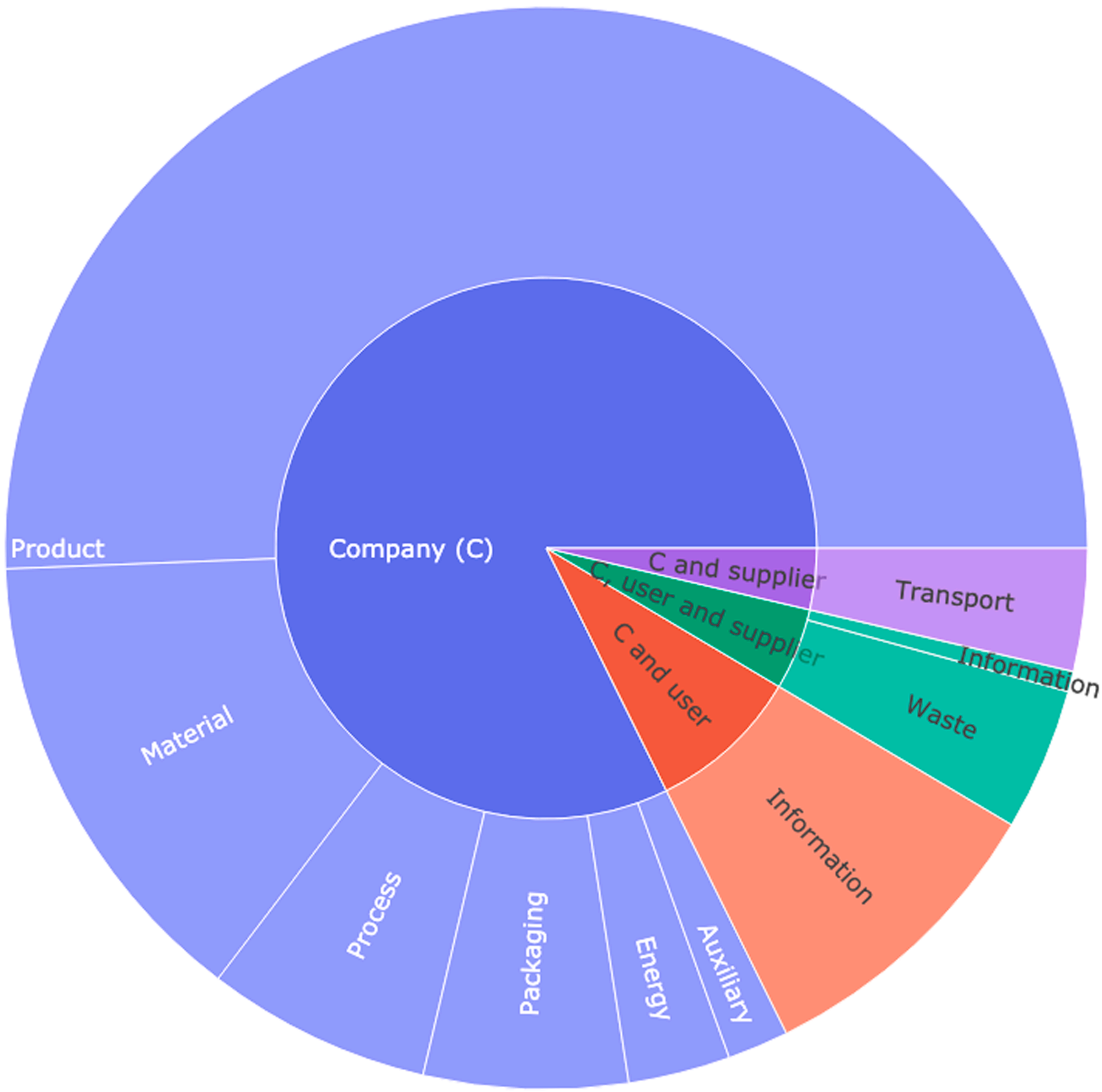

Fig. 4. Stakeholder involvement in the eco-design process.

these cases, while the company has certain control regarding the upstream suppliers such as ones providing auxiliary, energy, and materials, it has limited influences on the providers of transport service, e.g. local, regional and global transportation infrastructure and network. Guidelines relevant to transport improvement are classified into shared responsibility between the company and the suppliers.

Guidelines related to information such as provide the manuals; provide information and clear instructions about cleaning, maintaining, disassembling, and disposing the product; include labels and instructions for safe handling of toxic materials, for recyclability; etc. belong to the group of shared responsibility between the company and the users. By following the instructions, manuals and documentation on preferable behaviour, appropriate storage, cleaning and maintenance, disassembly and safe disposal of the product, the end-users can reduce the environmental impacts during the use and end-of-life stages, aiming at the eco-design of the technologies. Although these actions (e.g. provision of manuals, information and instructions) are implemented by the company, their final impacts, i.e. whether the recycle rate is increased or not, or whether the unused product is properly disposed or not, totally depend on the user behaviour.

There are several guidelines concerning the involvement of company, users, and suppliers, which mostly aim at improving the waste management, such as facilitating the appropriate treatment and safe disposal of waste, minimizing the generation of waste and atmospheric emissions. This group of guidelines also concerns the involvement of all stakeholders into the eco-design process.

There are several strategies for enlisting the help of suppliers and end users (which have been done in the NEST (Network for Sustainable Energy Transition) Spoke 1 project). First, the list of potential stakeholders, such as manufacturers, researchers and technology developers, designers, and media, is prepared. These stakeholders should be included into the eco-design process by participating into several co-creation activities of the living labs. Some examples of these co-creation activities are organizing seminars, workshops, meetings, and lab visits among different stakeholders including both the engineers, technology developers and environmental analysts, so that they can all contribute to the eco-design process. There is a website for communicating and disseminating the information about eco-design (of solar energy technologies), where persons who are interested into this topic can contact. Besides, a tool for supporting eco-design was developed and reviewed (tested) by the stakeholders. The testing procedure of the tool started with the engineers and technology developers who directly work in the solar energy field and then extended to the broader stakeholders.

Users and design stages

The implementation of eco-design guidelines requires the collaboration inside the company, including designer, engineer, environmental manager and business manager. These people are also the key users of the eco-design guidelines who applied the guidelines during certain period of a product development. At the beginning of product development process, e.g. the preparation stage, the contributions of design managers, sustainability experts, design engineers are needed. After that, industrial designers and design engineers play the most important role during the concept and embodiment design stages. During the detail design stage, apart from industrial designers and design engineers, the contribution of environmental specialists is crucial for practicalizing eco-design concepts into the product development process. At the design finalization stage, the design managers, environmental managers, and design engineers should work together to integrate all aspects of engineering design, industrial design, and aesthetic design into the product, with consider of environmental aspects. Contribution of business manager during the first and the last steps is required to have a clear view on economic benefit of implementing eco-design concept into the product development process. Besides, the business manager plays an important role in implementing guidelines that concern the involvement of external stakeholders such as suppliers and users. Fig. 5 presents the link of eco-design guidelines with guideline users and design stages.

3.3. Integration of LCA in eco-design

For the eco-design of a product, the most common tool is LCA. LCA works well for eco-assessment by quantifying and evaluating the life cycle environmental impacts of the product and pointing out the hotspot component/ stage, which contributes the largest share of life cycle environmental impacts, as well as the critical impact, which accounts for a major part of the endpoint impact. The identification of hotspot and critical impact are useful for eco-improvement of the product, by providing specific eco-design guidelines for the studied products. Therefore, integrating LCA results into the conceptual framework would provide detailed actions and measures for the eco-design of a specific solar energy technology.

Specific LCA based eco-design measures

Based on LCA results, there are several measures being suggested for eco-design of solar energy technologies, covering various life cycle stages and sub-components of the technology. During the manufacturing stage of solar PV systems, new materials are recommended due to its natural abundancy and relatively low cost. For examples, Jones et al (Jones et al., 2024). studied a copper-based chalcogenides made from copper, zinc and tin. Due to its chemical properties in term of energy bandgap and absorption coefficient, the selection of this material as a PV material minimizes the thickness of the absorber layer, consequently reducing the relevant environmental impacts and costs related to the material. To bring the lab-scaled benefits of this material to the industrial scale, the fabrication process needs to be optimized to obtain the material with the lowest environmental impacts and costs.

Zhang et al (Zhang et al., 2015). studied perovskite solar cells, due to their low cost and excellent technical performance. In general, perovskite solar cells are better than conventional solar cells, based on silicon and cadmium tellurium, in terms of energy production, energy payback time and GHG emissions. Despite of containing lead, a toxic material in the perovskite precursors, it was clarified that lead only contributes to 1.14% of human toxicity potential. For the future large-scale, industrial application of perovskite solar cells, perovskite precursor, which contributes up to 65% of embodied energy, 31% of embodied material, and 50% of most environmental impact categories, must be further studied.

In case of concentrating solar technologies, Albertí et al (Albertí et al., 2019). compared life cycle environmental impacts of solar thermal system for domestic hot water and natural gas heating system, and examined several eco-design measures. Two of these eco-design measures are related to changing the materials, and one of them is to use recycled materials for the collector frame. By changing the copper tubes into galvanized steel ones, the system is heavier, the primary energy demand slightly increases by 0.9%, but the acidification potential decreases by 5.7%. In contrast, the change of covering material from glass to polycarbonate reduce the primary energy demand by 0.9% and consequently reducing global warming potential by 1.5%. However, the acidification potential slightly increases by 0.6%. In the third eco-design measure, the existing collector frame which is made from 90% virgin and 10% of secondary aluminium, is changed into a similar material with higher recycled proportion, e.g. 20% of virgin and 80% of secondary aluminium. This eco-design measure brings the best effect, with the reduction in all assessed impact categories such as acidification (−4.6%), eutrophication (−3.5%), global warming (−2.7%), and

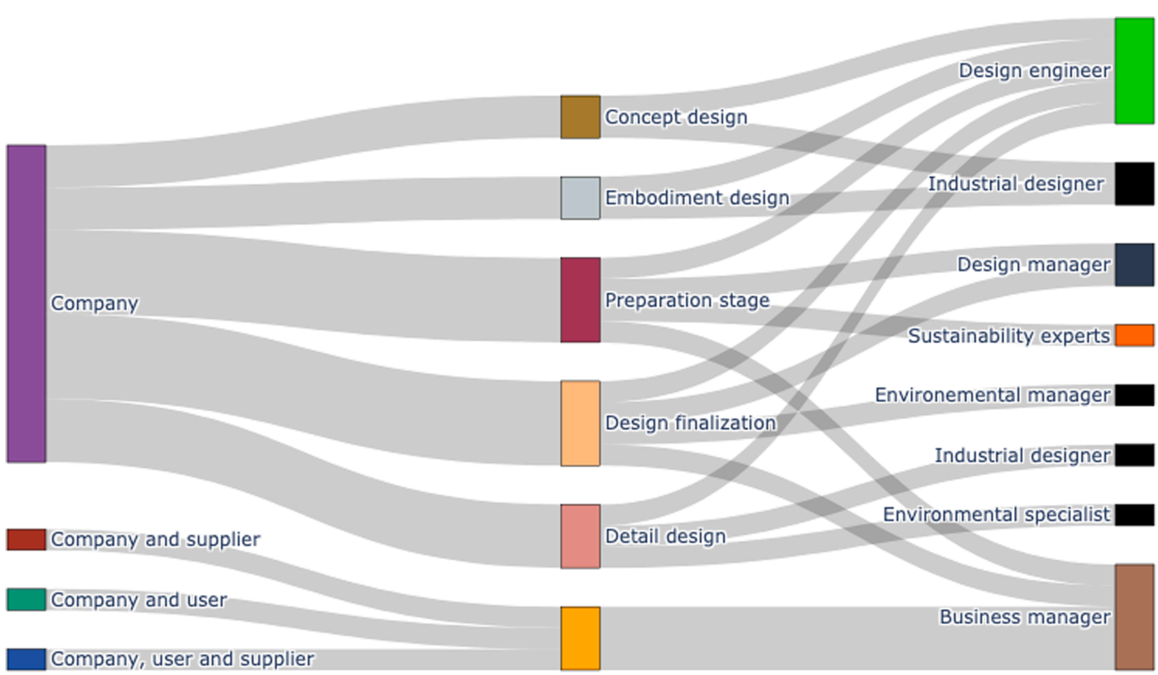

Fig. 5. Guideline users and design stages.

primary energy demand (−2.4%).

Olmedo-Torre et al (Olmedo-Torre et al., 2018). conducted an LCA and techno-economic analysis to identify the best heat transfer fluids used in solar concentrating power plants. In this case, there are some trade-offs of changing from one auxiliary (e.g. oil, in this case study) to another one for transferring the heat from solar energy. Specifically, Malotherm SH has the best environmental profile, in all three aspects of human health, ecosystems and resources, while Therminol 66 is the worst oil in term of environmental aspect. However, when the assessment is extended to their technical efficiency and economic aspect, Dowtherm A becomes the best option due to its cheap price and good performance. The best solution from the environmental point of view (Malotherm SH) becomes the least favourable option overall due to its high cost.

Moreover, organic materials are encouraged due to its lightweight and flexibility. Tsang et al (Tsang et al., 2016). compared the life cycle environmental impacts organic solar cells and silicon solar cells and identified that their environmental impacts are 55% and 70% lower than those of their counterparts for solar rooftop and portable solar charger. The difference in the reduction of environmental impacts is due to the long-term or short-term use of the cells. Due to the short lifetime of organic solar cells, the cells need to be replaced several times to fulfil 25 years of operation of a solar rooftop, while there is no replacement needed for 5 years of use in case of portable solar charger. To achieve the industrial scale of organic solar cell, the lifetime of 5 years and efficiency of 5% must be obtained. Moreover, it will be more suitable to use organic solar cells in simple and short-term applications without concerning a lot of ancillary components and requiring less resources such as the portable solar charger.

Eco-design measure that may go beyond the material, auxiliary or energy use for the cells, is to rethink the structure of the product from the single junction solar cells to tandem solar cells. Tandem solar cells comprise of several absorber layers, so that each layer absorbs the different bandgaps, maximizing the absorption ability of the whole cells. The efficiency of tandem solar cells may reach 33.7% (KAUST cells based on perovskite and silicon), with the average of 22.26% for all tandem cells being researched and reported from 2008 to 2023 (NREL, 2023). In order to bring these research results out of the lab and upscale the technologies, the fabrication process of tandem solar cells needs to focus on energy and material efficiency. For example, Blanco et al (Blanco et al., 2020). suggested that the metalorganic vapor phase epitaxy process for growing the absorber layer of the silicon-based tandem solar cells should be energy-efficient by minimizing the thermal mass that must be heated, increasing the growth rate and reducing the growth time. By improving the energy efficiency, several life cycle environmental impacts of the silicon-based tandem solar cells such as climate change, human toxicity and freshwater toxicity, will be reduced.

Another example of 'rethink' eco-design measure is to combine various solar energy technologies. Bahlawan et al (Bahlawan et al., 2019). suggested a hybrid system of solar PV and concentrating solar power in Italy, composing of PV panel, solar thermal collector, combined heat and power system, absorption chiller, heat pumps and thermal energy storage. Taking into account the cumulative energy demand into the technical design, the optimal hybrid system has a larger area of solar PV and larger size of combined heat and power system, reducing the grid electricity consumption and bringing a higher primary energy savings of 12%. Dumortier and Haussener (Dumortier and Haussener, 2015) examined the energy yield and GHG emissions of a hybrid system of concentrator, solar PV, fuel cell and cooling system, and identified that GHG emissions of hydrogen produced by this system is seven times lower than that produced by PV cells, biomass gasification and natural gas steam reforming. Royo et al (Royo et al., 2016). combined building integrated PV (BIPV) and phase change material to reduce GHG emissions and other environmental impacts. This combination prevents the occurrence of hot spots and reduces premature degradation, consequently reducing material consumption, energy use and GHG emissions (−62kgCO_2eq per m^2).

The summarized guidelines with some specific eco-design measures are presented here, with explanations of their corresponding stages and components in Fig. 6. The complete list of guidelines is provided in the supporting information SI1. To use this complete guideline, the users may select their role in the designing process (e.g. designer or business manager), the designing stage they are conducting (e.g. concept design, detail design, design finalization, and etc.), and even the life cycle stage they are aiming at (e.g. production, use, end of life or all life cycle stages), then the appropriate design guidelines will be displayed.

- R1-Rethink of material, auxiliary, energy and process: change into new materials constituting a solar cell, for example chalcogenides, perovskite, organic; and choose the heat transfer fluid with the best environmental profile and most reasonable cost; and increase the efficiency of solar cell fabrication process. For example, a portable solar charger made of organic materials has the lower environmental impacts (70%) compared to a similar charger made of silicon (Tsang et al., 2016).
- R1-Rethink of product: changing the structure of solar cells from single junction to multi junction; developing hybrid system of solar PV and concentrating solar power, or solar energy technologies with other technologies (hydrogen production, water desalination, etc.) to maximize their energy production benefits. In solar PV cells, the perovskite and silicon-based tandem cells have much higher power conversion efficiency than the average mono crystalline silicon cells, e.g. 33% (NREL, 2023) compared to 20% (IEA, 2024a). Besides, combination of solar PV and concentrating solar power brings a primary energy savings at 12% (Bahlawan et al., 2019).
- R2-Reduce of material and energy: reduce the use of materials, energy and components constituting the product; reduce packaging.
- R3- Reuse of components: Facilitate the separation of components for reuse, encourage reuse of components especially resource intensive components; reuse packaging. In cases the components cannot be directly reused, they may be recycled to recover such materials as aluminium, copper, and steel. This is very common for solar PV mounting frames, with the conversion rate of 97% for aluminium and 90% for steel. The recycling of component and recovery of metals are also applicable for some sub-systems and other components of solar PV such as inverter and cabling. For inverter, 97% of aluminium, 76% of copper and 90% of steel are recovered and reused. Similarly, 76% of copper from recycling cables are reused (Tsang et al., 2016).
- R4-Repair of components: Use durable components to avoid repair; protect the products from dirt; minimize required maintenance; and facilitate the cleaning and maintenance of the products.
- R5-Refurbish of product: Facilitate the refurbishment of the product.
- R6-Remanufacture of product: Facilitate the remanufacture, upgrade and adaptation of the products.
- R7-Repurpose of the product: no available guidelines on repurpose of solar energy systems.
- R8-Recycle of material: use recycled materials for solar collector frame. This eco-design measure reduces 4.6% of acidification, 3.5% of eutrophication, 2.7% of global warming and 2.4% of primary energy demand compared to using virgin materials (Albertí et al., 2019). For solar PV, the use of solvent in manufacturing TiO_2 nanotube electrode and perovskite precursor contributes the largest part of the life cycle impacts. Therefore, solvent recycle, and reuse are encouraged to reduce the environmental impacts of perovskite solar cells, because the energy and material requirements for recycling solvent are smaller than the production of virgin solvent. The recycled solvent can be reused either in the same manufacturing process or in other industries such as semiconductor manufacturing (Zhang et al., 2015).
- R9-Recover of material and energy: facilitate the access to components containing non-recyclable, non-compatible, toxic, valuable,

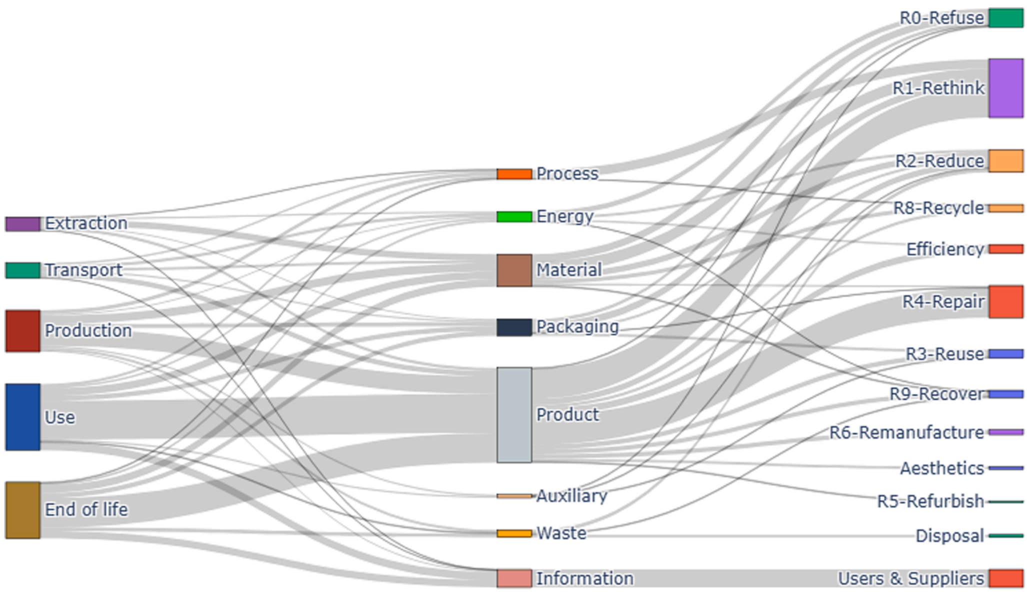

Fig. 6. Eco-design guidelines and corresponding life cycle stages and components.

rare and critical materials for recovery; recover energy from the incineration of waste. The incineration of plastic waste may generate 4 MJ of electricity per kg of plastic waste. For organic PV cell, with PET substrate, the energy recover may reach 4.95 MJ of electricity per kg of incinerated organic PV panel (Tsang et al., 2016).

Energy indicators and eco-design of solar energy technologies

Apart from the product and its constituting components, eco-design should also take into account the materials, energy, auxiliary and process. The current eco-design guidelines put priority on improving the environmental profile of the product by reducing the impacts from materials (Refer to Fig. 2 and Fig. 5 which indicate a relatively large number of guidelines on materials, compared to energy, auxiliary and process). During the eco-design of solar energy technologies, it is crucial to consider the energy aspect with more attention, as solar energy technologies involve both energy production and consumption, being different from other products and services which either consume or produce energy.

Moreover, the inclusion of energy indicators in LCA can actively inform and guide the eco-design process. Energy is the input for many processes; therefore, the improvement in energy technologies would lead to change during the design of other products towards an environmental-friendly future. The inclusion of the energy-related indicators does not just aim at reducing non-renewable energy consumption, but also reflect in other environmental impacts such as climate change, material consumption, eco-toxicity, human toxicity, etc. In such case, the manufacturers and businesses will not only achieve an energy label but can also aim at the eco-label for their corporate social responsibility.

There are various indicators related to energy aspects of the technologies such as cumulative energy demand (CED), energy return on investment (EROI), net energy ratio (NER), energy payback time (EPBT) and resource use, fossil (ADP_f), several of which have been recommended by the International Energy Agency (IEA) for solar PV. The net energy analysis should be conducted for CED and EROI, following the equations (1), (2), (3) and (4) (Raugei et al., 2016), and the EPBT can be quantified by applying the equations (5) (Frischknecht et al., 2016). NER is similar to EROI, indicating the ratio of energy produced by the PV system and energy required to develop and operate it. ADP_f is calculated following equation (6). It should be noted that ADP_f is also called by different names, for examples fossil fuel depletion, and measured by different metrics, for examples MJ surplus, depending on the life cycle impact assessment methods. Table 2 presents recommended energy indicators for eco-design of the solar energy technologies.

Explanations of the equations:

PE is total primary energy from the nature, PE_{nr} is non-renewable primary energy from the nature (MJ),

Inv is additional energy investment from human socio-economic activities, Inv_{nr} is additional non-renewable energy investment (MJ),

Out_{el} is energy delivered to society (energy output) in the unit of

Table 2
Key performance indicators of solar energy technologies.

No	Indicator	Explanation	Equation
1	Cumulative energy demand (CED) (MJ/MJ)	Total primary energy harvested from the environment to produce a given amount of usable energy carrier.	$CED = (PE + Inv)/Out_{el}$
2	Cumulative non-renewable energy demand (CED_{nr}) (MJ/MJ)	Total non-renewable primary energy harvested from the environment to produce a given amount of usable energy carrier.	$CED_{nr} = (PE_{nr} + Inv_{nr})/Out_{el}$
3	Energy return of Investment in electricity (EROI)	Ratio of the amount of electricity delivered from the PV system to the total amount of energy invested in finding, extracting, processing and delivering that electricity.	$EROI_{el} = Out_{el}/Inv$
4	Energy return of Investment in equivalent primary energy ($EROI_{PE\text{-}eq}$)	Ratio of the amount of equivalent primary energy delivered from the PV system to the total amount of energy invested in finding, extracting, processing and delivering that electricity	$EROI_{PE-eq} = Out_{PE-eq}/Inv = \left(\frac{Out_{el}}{\eta_G}\right)/Inv$
5	Energy Payback Time (EPBT) (year)	Period required for the PV system to generate the same amount of primary energy that was used to produce the system itself	$EPBT = \sum E_i / \left(\left(\frac{E_{gen}}{\eta_G}\right) - E_{O\&M}\right)$
6	Resource use, fossil (ADP_f) (MJ)	Depletion of non-renewable (fossil) resources and deprivation for future generations	$ADP_f = \sum F_j \times CF$

electricity (MJ),

E_i is the primary energy demand of all life cycle stages of PV systems, excluding operation and maintenance (MJ),

$E_{O\&M}$ is the primary energy demand for operation and maintenance (MJ),

E_{gen} is the annual electricity generation (kWh),

η_G is the grid efficiency (kWh/MJ).

F_j is the total amount of fossil fuels consumed during all life cycle stage of PV system (kg)

CF is the characterization factors of corresponding fuels. For quantifying ADP_f, it is recommended to apply the Environmental Footprint (EF) Impact Assessment of the European Commission, which is based on CML2002 for reserve base with a longer time horizon and potential mining technology improvement and feasible exploitation of sub-economic deposits (EPLCA).

Some LCA methodological recomendations

There are existing methodological guides to support for the application of LCAs for eco-design of solar energy technologies. The IEA provided several methodological guidelines for quantifying and analysing the life cycle environmental impacts (Frischknecht et al., 2016) and life cycle energy of solar PV under Task 12 and Task 13, for example guidelines on Net Energy Analysis (Raugei et al., 2016). Besides, the Product Environmental Footprint Category Rule (PEFCR) is an effective methodological guideline to support the eco-design of solar energy technologies (Wade et al., 2018). This methodological guideline has been verified in several case studies for solar PV modules (Khan et al., 2024) and for concentrating solar technologies (Luu et al., 2024).

It is recommended that for the eco-design of solar energy technologies, these IEA and PEFCR methodologies should be followed. First, the functional unit of kWh of electricity or MJ of heat should be selected, with the functional unit of m^2 of panel for complementation. The selected function units ensure the fair comparison among different solar energy technologies, as well as solve the problem of lack of data, e.g. electricity production, of innovative, lab-scaled technologies. Second, the system boundary should cover from cradle to grave, with consideration of recycling scenarios (European Commission. Joint Research Centre, 2024). This system boundary may be narrowed to cradle to gate, with focusing on the choice of material, energy, and fabrication process for innovative, lab-scale technologies. Ideally, all life cycle environmental indicators of PEFCR (EC) should be quantified and assessed. If not, the most critical environmental impacts related energy, carbon footprint, resource consumption, and toxicity should be considered. The quantification of energy indicators is discussed in the 3.3 with IEA's guidelines, while for other environmental impacts such as carbon footprint, resource consumption, and toxicity, the PEFCR methodology (EC) should be followed.

Regarding the databases, apart from the popular inventory database such as EcoInvent (Ecoinvent), there are several life cycle inventory databases available for solar energy technologies, for examples the well-developed inventories of solar PV supply chain of IEA (Frischknecht, 2020), data for recycling of the solar PV module (IEA, 2024b).

3.4. Illustrative cases of applying the conceptual framework to guide the eco-design of solar energy technologies

The combination of the general guidelines and LCA can be applied on eco-design of BIPV (Luu et al., 2025). The general guidelines are used for brainstoming the activities concentrating on sub-components of the product such as materials, energy, components and the life cycle stages. At the same time, using LCA with scenario analysis, sensitivity analysis and uncertainty analysis, different BIPV modules are examined to identify the module with the lowest environmental impacts, considering their energy generation and transmittance. On the material scale, various materials for absorber layer of BIPV modules, such as silicon and perovskite may be tested for the low impact materials, to avoid the toxic substance and encourage the abundant materials. On the product scale, different types of solar (colour) glass may be studied to consider the aesthetics, quality and efficiency of the product. Apart from the production stage, the end-of-life stage may contribute to the eco-design of the BIPV module, through the recycling of the decommissioned mounting frames, glass, and PV cells. At the end of the eco-design process, four general and 11 actionable suggestions have been estabished:

On the product scale, the eco-design needs to consider the specific application of BIPV modules to balance the benefits of electricity generation, weather protection and aesthetic value, by (1) using silicon-based BIPV modules for applications that does not require high transmittance, (2) using frameless PV laminates and special mounting system for fully integrated BIPV roof installation, (3) applying thin-film layer on rigid substrate for rooftop installation and (4) using colour glass, perovskite materials and combinations of materials for applications which require high transmittance.

On the component scale, the eco-design need to focus on environmental and economic hotspots such as PV cell, EVA, mounting system and glass by (5) increasing the energy efficiency of cell manufacturing for silicon-based PV cells, sourcing electricity for cell manufacturing from clean and renewable energy sources, (6) improving the material efficiency and futher studying new materials for EVA and mounting system, and (7) further studying to reduce the cost of colour glass and improve the efficiency of cell manufacturing for perovskite solar cells.

On the material scale, the eco-design should futher study innovative materials and combinations of materials for absorber layer, electron transport layer and glass, by (8) improving the efficiency and lifetime of perovskite materials by combining it with other materials, and (9) further studying to combine materials for different layers of the cells.

Considering the whole life cycle, BIPV modules should be recycled when they reach their end of life, with clear eco-design actions such as (10) increasing the efficiency of the recycling process and (11) encouraging the use of recovered and recycled materials and modules.

Another example is to apply the framework in solar PV and concentrating solar power (CSP) (Luu et al., 2026). Similarly, general guidelines aim at skimming the eco-design directions on technical improvement, materials, components and fabrication process of solar energy technologies. LCA is applied in form of comparative LCAs with hotspot identification. Apart from quantitative LCA results, several eco-design measures are proposed in this case study, for solar PV made from perovskite and organic materials, such as (1) improving efficiency and lifetime of the cells, (2) changing materials fabrication processes, (3) reducing envitonmental impacts from electron transport layer, absorber and electrode. For CSP, some eco-design measures include: (1) optimizing the plant configurations, (2) minimizing the use of natural gas, (3) reducing environmental impacts of collector field, power generation unit and heat transfer fluid.

3.5. Discussion

The conceptual framework includes two main components of general guidelines and LCA. The general eco-design guidelines for solar energy technologies are quick and simple tools for screening the eco-design action to improve the eco-profile of solar energy technologies. It covers the whole life cycle of the product, making them a good start for brainstorming potential eco-design measures of every stage from material extraction, production, transportation, and end of life. The guidelines provide recommendations on the stakeholders should be involved, the users of guidelines and the design stages when each guideline should be applied. This will help the users of these guidelines, either designers, engineers, environmental managers, or business managers to take the best benefit from the guidelines. In case of being combined with LCA of the specific solar energy technologies, for example perovskite solar cells, tandem solar cells, parabolic trough concentrating solar technologies, the conceptual framework would give out the specific actions to improve the eco-profile of that specific technology.

The development of the framework is an on-going activity. Since they are formulated, the guidelines have been shared and tested for several times among more than 200 stakeholders of the NEST Spoke 1 project, including students, researchers, industries, and the press who work in solar PV and solar energy sector. They were first presented at the project meeting and winter school in Brixen, Italy in February 2025 for the introduction of the tool, and then presented in the project meeting in Cagliari, Italy in June of the same year for the update. Meanwhile, the LCA component is implemented for several NEST products such as perovskite solar cells, tandem solar cells, BIPV, CSP and some electronic devices.

Comparing to the existing frameworks on environmental management and LCA such as ISO 14001, ISO14040, ISO14044 standards and PEFCR method, this proposed framework focuses on eco-design, e.g. integration of environmental aspect into the product design. All these frameworks, either LCA or eco-design share the similarity in applying the life cycle thinking approach and covering various stage of the product's life cycle from acquisition of inputs, production, use, transport, and end-of-life. However, they are slightly different in the applications. The concept underlining the above ISO standards and PEFCR is to quantify and assess the life cycle impacts of the product system, or eco-assessment, while this proposed framework aims at the eco-improvement of the product.

Besides, there are several international and regional eco-design frameworks, such as ISO 14062 standard, ISO Guide 64, and CEN4 standard (European Committee for Standardization). The ISO 14062 and ISO Guide 64 are international standards (and were withdrawn), while CEN4 is applicable for EU countries. Both these eco-design frameworks and the proposed guidelines provide different considerations being relevant to material selection, energy efficiency, material reuse and recycling, use of product, information exchange or communication to customers on the intended use of a product, and environmental aspects. While the existing eco-design frameworks cover all types of products, the proposed guidelines in this study are specifically designed for solar energy technologies, with eco-design measures applicable for solar PV and concentrating solar power.

For the industry practitioners, it is recommended that they should conduct a stepwise procedure for the eco-design of solar energy technologies. First, these general guidelines should be used to brainstorm all potential actions to improve the environmental profiles of the technologies. Depending on the specific users, the stakeholders and the life cycle stages that they are aiming at, various guidelines can be filtered to save their time and effort. Second, LCA should be conducted to identify the specific measures or actions which are most appropriate for their own product. Some proposed actions for solar energy technologies include:

- Rethink of the materials for solar cells and concentrating solar power; changing the structure of the cells, hybridizing the technologies for the most efficient system;
- Reduce of materials, energy and packaging;
- Reuse and repair of components;
- Refurbish and remanufacture of product; and
- Recycle and recover of materials and energy, and encourage to the use of recycled materials.

By applying the proposed conceptual framework and implementing the eco-design actions at the early stage of product development process, the environmental footprint of solar energy technologies would be reduced. The benefits do not limit in the technologies themselves but extend to the sub-components constituting the technologies such as material, energy, manufacturing process, waste, etc., covering all life cycle stages. Apart from envionmental benefits, implementing the eco-design actions would bring the economic benefits for the manufacturers by saving operational cost on material and energy, and for the users by extending the product's lifetime.

Eco-design has been defined as the integration of environmental aspects into all stages of product development process to aim at the most environmental-friendly product over its life cycle (UNEP, 2021), i.e. the main focus is on the eco-improvement of products, without considering the economic aspects. However, the eco-improvement of product closely links to reduction of materials and resources, thus leading to cost minization. In order to account for the economic aspects, the conceptual framework may include the life cycle costing (LCC) for optimizing the cost of product over its life cycle. In this way, the framework is extended to cover both environmental and economic aspects, to denote the design and redesign of the product, simultaneously considering the environmental performance and cost of the product over the entire life cycle.

43% of the current solar PV sustainability standards' goals and targets contribute to the SDG12 on responsible consumption and production, indicating the important role of sustainable production and consumption in the solar energy sector (Espinosa et al., 2025). The eco-design guidelines touch both the production and consumption stages during the life cycle of the product, minimizing the environmental impacts of the product. Besides, through the eco-design measures, the generation of waste is minimized, aiming at the end-of-life stage of the product. It is recommended that in order to enhance the sustainability sector, the circular and social practice should be integrated into the design of solar energy product (Espinosa et al., 2025). This will improve the resource efficiency, minimize waste, and cover both sustainability and circularity of the solar energy product. In this case, the eco-design of the product is extended to the concept of "Design for Sustainability and Circularity". At the same time, the tools for supporting the sustainability of the product should be refined (Espinosa et al., 2025). The tool will not only relevant to the eco-design guidelines for environmental sustainability but also integrates the economic and social aspects of the solar energy product. An example of integration of the economic aspect is to consider the cost of the emerging solar energy technology, while the social aspect may be extended from the stakeholder involvement into the design process of the product (as being implemented in the proposed framework) to the social equity in energy sector (e.g. the deployment of solar energy technology helps to improve the energy access), corporate social responsibility of suppliers in the solar energy supply chain, and etc.

4. Conclusion

The paper presents a conceptual framework to guide the eco-design of solar energy technologies. The framework includes a list of general eco-design guidelines, in combination with LCA implementaion. The general eco-design guidelines being compiled from the literature on solar energytechnologies. There are 164 guidelines covering five main stages of the technology's life cycles, including material extraction, production, transportation, use and end of life, and several main components constituting or contributing the manufacture of technologies such as material, auxiliary, energy, manufacturing process, packaging, product, waste and information (shared with users). About 80% of the eco-design guidelines are relevant to 'R' measures, for examples refuse (the packaging), rethink (the modular structure of the product), reduce (the use of material), reuse (the component), repair, refurbish and remanufacturing (the product), recycle (the components and materials) and recover (the energy from waste). Some examples of practical eco-design measures that can be applied for solar energy technologies are changing into new materials for solar cells such as chalcogenides, perovskite, and organic to increase energy efficiency, reduce the environmental impacts and delivers the most economic feasibility; recycle components and using recycled materials for solar collector frame; recover energy from incineration of waste, etc. Applying these measures into the solar energy technology's development will increase the efficiency of the technology, consequently reducing its life cycle environmental impacts per unit of energy production.

The general guidelines provide a list of eco-design measures to be implemented by both internal and external stakeholders of the manufacturing companies during various design stages. Internal stakeholders such as product designers, engineers, environmental specialists, and business managers may apply these guidelines to quickly identify the most suitable measures for solar energy technologies to be implemented at the proper timing. External stakeholders of the manufacturing company, for example upstream suppliers of materials and energy, and customers or end-users, though do not directly use the eco-design guidelines, can contribute to the eco-improvement process of the solar energy technologies through some activities such responsible consumption during the use stage and responsible treatment of decommissioned technologies during their end of life.

For a particular product or technology, especially the innovative solar energy technology, these general eco-design guidelines are inadequate to propose specific, actionable measures to improve the eco-profile of the technology. In this case, it is suggested that an LCA should be conducted to point out the eco-design measures that are suitable to the context of such product and its lab or manufacturing facility. The LCA study can be a simplified LCA if the time and budget is constrained, or it can be a complete LCA, or even an integrated LCA by combining LCA with engineering, simulation, or modelling tools. Ideally for the EU context, the LCA should be implemented according to the PEF guidelines and following the energy-related indicators of IEA.

The conceptual framework indicated that eco-design of solar energy technologies is most effective when general guidelines are combined with LCA. The general guidelines are structured by life cycle stages, stakeholders' role, and design phases for extracting the most suitable guidelines, while the hotspot identification, scenario analysis, sensitivity analysis and uncertainty analysis of LCA enables the transition from genenal directions to technology-specific, actionable measures with quantified results. The analysis of 164 guidelines confirms that about 80% of eco-design measures are aligned with circular economy principles, concentrating on the end-of-life stage. In such cases, design for disassembly, recyclability, and material recovery should be systematically prioritised from the early stage during the technology development pathway. The energy indicators encompassing CED, EROI, EPBT, and ADPf are identified as the fundamental reporting basis for LCA-based eco-design of solar energy technologies, following the IEA and other PEFCR methodological guidelines.

The application of the proposed framework at manufacturing companies and their supply chains requires a shared responsibility distributed across internal departments and external actors from upstream material and energy suppliers to downstream waste treatment service providers. For energy industry and technology developers working on emerging photovoltaic technologies, the conceptual framework offers a mechanism to embed environmental criteria into product development at an early stage for increasing the competitiveness of commercial technologies and upscaling emerging technologies. For policymakers responsible for the implementation of the Eco-design Directive and other solar sustainability standards, it is a practical reference for the sustainable development of technology-specific regulatory requirements for solar PV and CSP. For educational institutions, academics and multi-stakeholder innovation projects, it plays the role of both a teaching and research instrument and a co-creation tool to apply across a wide range of technological maturity levels, technology deployment contexts, and regulatory environments to support the transition to a low-carbon, circular economy.

Institutional Review Board Statement

Not applicable.

CRediT authorship contribution statement

Le Quyen Luu: Writing – review & editing, Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **Francesco Guarino:** Writing – review & editing, Writing – original draft, Resources, Data curation. **Sonia Longo:** Writing – review & editing, Writing – original draft, Resources, Methodology. **Maurizio Cellura:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Informed Consent Statement

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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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2026.109425.

Data Availability

The data is provided in the supporting information

References

Aktekeli, B., Aktaş, M., Koşan, M., Arslan, E., Şevik, S., 2025. Experimental study of a novel design bi-fluid based photovoltaic thermal (PVT)-assisted heat pump dryer (Jan). Renew. Energy 238, 121971. https://doi.org/10.1016/j.renene.2024.121971.

Albertí, J., et al., 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 (May). Sustain. Cities Soc. 47, 101467. https://doi.org/10.1016/j.scs.2019.101467.

Apel, C., et al., 2024. Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives (Feb). Curr. Opin. Green. Sustain. Chem. 45, 100876. https://doi.org/10.1016/j.cogsc.2023.100876.

Ardente, F., Beccali, G., Cellura, M., 2003. Eco-sustainable energy and environmental strategies in design for recycling: the software 'ENDLESS. Ecol. Model. 163, 101–118. https://doi.org/10.1016/S0304-3800(02)00418-0.

Ardente, F., Beccali, M., Cellura, M., 2004. F.A.L.C.A.D.E.: a fuzzy software for the energy and environmental balances of products (Sep). Ecol. Model. 176 (3–4), 359–379. https://doi.org/10.1016/j.ecolmodel.2003.11.014.

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 (Feb). Energy Procedia 158, 2834–2840. https://doi.org/10.1016/j.egypro.2019.02.046.

Baro, M., Borgohain, P., 2026. Design and performance analysis of Cs 2 Ag (Sb y Bi 1 - y) Br 6 perovskite solar cells: Insights from SCAPS-1D device simulations (Jan). Renew. Energy 256, 124225. https://doi.org/10.1016/j.renene.2025.124225.

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 (11), 4280–4290. https://doi.org/10.1039/D0EE01039A.

Campos-Carriedo, F., Pérez-López, P., Dufour, J., Iribarren, D., 2024. A parametric life cycle framework to promote sustainable-by-design product development: Application to a hydrogen production technology (Sep). J. Clean. Prod. 469, 143129. https://doi.org/10.1016/j.jclepro.2024.143129.

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 (11), 3069–3082. https://doi.org/10.1039/C5EE01269D.

EC, "Understanding Product Environmental Footprint and Organisation Environmental Footprint methods." [Online]. Available: ⟨https://circabc.europa.eu/ui/group/6e9b7f79-da96-4a53-956f-e8f62c9d7fed/library/537534a4-9c76-40a1-b488-e9127db2befd/details?download=true⟩.

Ecoinvent, "Ecoinvent Database Version 3.7." [Online]. Available: ⟨https://ecoinvent.org/the-ecoinvent-database/⟩.

EPLCA, "Environmental Footprint (EF) Impact Assessment." [Online]. Available: ⟨https://eplca.jrc.ec.europa.eu/EFVersioning.html⟩.

Espinosa, N., Sinha, P., Drozdiak, K., Wade, A., Heath, G., O'Neil, C., 2025. Review of PV Sustainability Standards 2025 (Aug). IEA PVPS - Int. Energy Agency Photovolt. Power Syst. Program.. https://doi.org/10.69766/BINS9725.

European Commission. Joint Research Centre, 2024. Review of the MEErP: methodology for ecodesign of energy related products. LU: Publications Office. Accessed: Apr. 12, 2024. [Online]. Available: ⟨https://data.europa.eu/doi/10.2760/24524⟩.

R. Frischknecht *et al.*, "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems," NREL/TP-6A20-73853, 1561526, 2020. doi: 10.2172/1561526.

Frischknecht, R., Heath, G., Raugei, M., Sinha, P., de Wild-Scholten, M., 2016. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity. International Energy Agency, IEA-PVPS T12-08:2016. ⟨https://iea-pvps.org/wp-content/uploads/2020/01/Task_12_-_Methodology_Guidelines_on_Life_Cycle_Assessment_of_Photovoltaic_Electricity_3rd_Edition.pdf⟩ ([Online]. Available).

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⟩ ([Online]. Available).

IEA, 2024a. Fact sheet: environmental life cycle assessment of electricity from PV Systems. IEA Photovolt. Power Syst. Program. (PVPS). https://doi.org/10.69766/ALGS2169.

IEA, "Advances in Photovoltaic Module Recycling Literature Review and Update to Empirical Life Cycle Inventory Data and Patent Review," 2024b. [Online]. Available: ⟨https://iea-pvps.org/wp-content/uploads/2024/06/IEA-PVPS-T12-28-2024-Report-PV-Recycling-LCI_EPRI.pdf⟩.

IRENA, 2024. Sol. Energy Overv. ⟨https://www.irena.org/Energy-Transition/Technology/Solar-energy#:~:text=The%20total%20installed%20capacity%20of,of%20any%20renewable%20energy%20source⟩ ([Online]. Available).

Jones, M.D.K., et al., 2024. Ecodesign of Kesterite Nanoparticles for Thin Film Photovoltaics at Laboratory Scale (Aug). ACS Sustain. Chem. Eng. 12 (31), 11613–11627. https://doi.org/10.1021/acssuschemeng.4c02841.

Kamp Albæk, J., Shahbazi, S., McAloone, T.C., Pigosso, D.C.A., 2020. Circularity evaluation of alternative concepts during early product design and development (Nov). Sustainability 12 (22), 9353. https://doi.org/10.3390/su12229353.

Khan, A.A., et al., 2024. The European Union's ecodesign directive – analysis of carbon footprint assessment methodology and implications for photovoltaic module manufacturers (May). Sol. RRL 8 (10), 2301011. https://doi.org/10.1002/solr.202301011.

Longo, S., Beccali, M., Cellura, M., Guarino, F., 2020. Energy and environmental life-cycle impacts of solar-assisted systems: The application of the tool 'ELISA (Jan). Renew. Energy 145, 29–40. https://doi.org/10.1016/j.renene.2019.06.021.

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 (Sep). Energies 17 (17), 4461. https://doi.org/10.3390/en17174461.

Luu, L.Q., Cellura, M., Guarino, F., Longo, S., 2025. Eco-design of emerging BIPV modules based on LCA and LCC (Oct). Energy 333, 137500. https://doi.org/10.1016/j.energy.2025.137500.

Luu, L.Q., Cellura, M., Guarino, F., Longo, S., 2026. Recommended actions for eco-design of solar energy technologies based on life cycle approach (Jun). Energy Rep. 15, 108961. https://doi.org/10.1016/j.egyr.2025.108961.

Martínez Leal, J., Pompidou, S., Charbuillet, C., Perry, N., 2020. Design for and from Recycling: A Circular Ecodesign Approach to Improve the Circular Economy (Nov). Sustainability 12 (23), 9861. https://doi.org/10.3390/su12239861.

Milousi, M., Souliotis, M., 2023. A circular economy approach to residential solar thermal systems (May). Renew. Energy 207, 242–252. https://doi.org/10.1016/j.renene.2023.02.109.

Munaro, M.R., Tavares, S.F., Bragança, L., 2022. The ecodesign methodologies to achieve buildings' deconstruction: A review and framework (Mar). Sustain. Prod. Consum. 30, 566–583. https://doi.org/10.1016/j.spc.2021.12.032.

NREL, "Cell PV Efficiency Emerging PV." 2023. [Online]. Available: ⟨https://www.nrel.gov/pv/cell-efficiency.html⟩.

Olmedo-Torre, N., Canals Casals, L., Amante García, B., 2018. Sustainable design of a thermosolar electricity generation power plant in Burkina Faso (Nov). J. Environ. Manag. 226, 428–436. https://doi.org/10.1016/j.jenvman.2018.08.043.

Pollini, B., Rognoli, V., 2021. Early-stage material selection based on life cycle approach: tools, obstacles and opportunities for design (Oct). Sustain. Prod. Consum. 28, 1130–1139. https://doi.org/10.1016/j.spc.2021.07.014.

Ratner, S., Gomonov, K., Revinova, S., Lazanyuk, I., 2020. Eco-design of energy production systems: the problem of renewable energy capacity recycling (Jun). Appl. Sci. 10 (12), 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," International Energy Agency. Report T1207: 2016 IEA-PVPS Task. 12. Report T1207: 2016.

Riondet, L., Rio, M., Perrot-Bernardet, V., Zwolinski, P., 2023. Assessing energy technologies sustainability: upscaling photovoltaics using absolute LCA. Procedia CIRP 116, 714–719. https://doi.org/10.1016/j.procir.2023.02.120.

Rossi, F., Heleno, M., Basosi, R., Sinicropi, A., 2020. Environmental and economic optima of solar home systems design: A combined LCA and LCC approach (Nov). Sci. Total. Environ. 744, 140569. https://doi.org/10.1016/j.scitotenv.2020.140569.

Royo, P., Ferreira, V.J., López-Sabirón, A.M., Ferreira, G., 2016. Hybrid diagnosis to characterise the energy and environmental enhancement of photovoltaic modules using smart materials (Apr). Energy 101, 174–189. https://doi.org/10.1016/j.energy.2016.01.101.

Russo, D., Rizzi, C., Spreafico, C., 2017. How to Build Guidelines for Eco-Improvement (in Smart Innovation, Systems and Technologies). In: Campana, G., Howlett, R.J., Setchi, R., Cimatti, B. (Eds.), Sustainable Design and Manufacturing 2017, 68. Springer International Publishing, Cham, pp. 879–887. https://doi.org/10.1007/978-3-319-57078-5_82 (in Smart Innovation, Systems and Technologies).

Sheikholeslami, M., Khalili, Z., 2024. Solar photovoltaic-thermal system with novel design of tube containing eco-friendly nanofluid (Feb). Renew. Energy 222, 119862. https://doi.org/10.1016/j.renene.2023.119862.

Siwiec, D., Pacana, A., 2024. Eco-Innovation Method for Sustainable Development of Energy-Producing Products Considering Quality and Life Cycle Assessment (QLCA) (Aug). Energies 17 (15), 3841. https://doi.org/10.3390/en17153841.

Sovacool, B.K., Stock, R., 2024. We struggle to survive': Exploring the whole systems energy injustices of solar photovoltaics in India (Jul). Electr. J. 37 (6), 107426. https://doi.org/10.1016/j.tej.2024.107426.

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 (Nov). Sol. Energy Mater. Sol. Cells 156, 37–48. https://doi.org/10.1016/j.solmat.2016.04.024.

UNEP, 2021. Term Eco-design ([Online]. Available). ⟨https://www.eea.europa.eu/help/glossary/eea-glossary/eco-design#:~:text=Eco%2Ddesign%20considers%20environmental%20aspects,throughout%20the%20product%20life%20cycle⟩.

Vilochani, S., McAloone, T.C., Pigosso, D.C.A., 2024. Consolidation of management practices for sustainable product development: a systematic literature review (Mar). Sustain. Prod. Consum. 45, 115–125. https://doi.org/10.1016/j.spc.2024.01.002.

Wade, A., Stolz, P., Frischknecht, R., Heath, G., Sinha, P., 2018. The Product Environmental Footprint (PEF) of photovoltaic modules—Lessons learned from the environmental footprint pilot phase on the way to a single market for green products in the European Union (Aug). Prog. Photovolt. Res. Appl. 26 (8), 553–564. https://doi.org/10.1002/pip.2956.

Yang, D., Vezzoli, C., 2024. Designing environmentally sustainable furniture products: furniture-specific life cycle design guidelines and a toolkit to promote environmental performance (Mar). Sustainability 16 (7), 2628. https://doi.org/10.3390/su16072628.

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 (Nov). ChemSusChem 8 (22), 3882–3891. https://doi.org/10.1002/cssc.201500848.