Science of the Total Environment 908 (2024) 168019

Contents lists available at ScienceDirect

Science of the Total Environment

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

Review

A review on life cycle environmental impacts of emerging solar cells

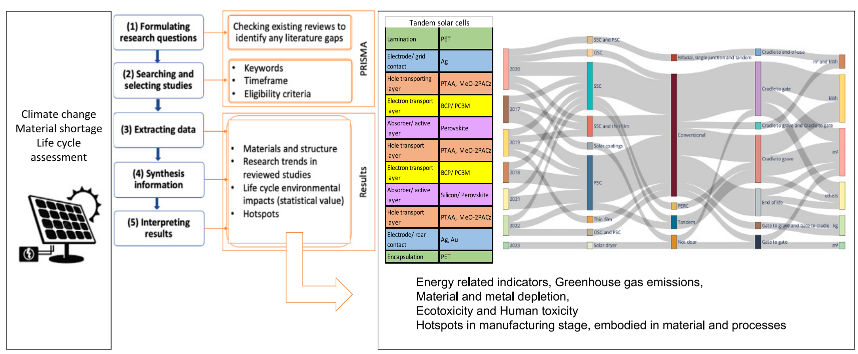
Maurizio Cellura, Le Quyen Luu *, Francesco Guarino, Sonia Longo

Department of Engineering, University of Palermo, Viale delle Scienze Ed.9, 90128 Palermo, Italy

HIGHLIGHTS

- Common indicators include energy, greenhouse gas, material, and toxicity.
- Manufacturing process is the hotspot for conventional and emerging solar cells.
- LCA method and production scales cause large range in environmental results.
- Eco-design is crucial in solar cell development to minimize environmental impacts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Solar PV
Solar thermal
LCA
Eco-design
Material

ABSTRACT

The development of solar technologies requires increased efficiency in converting solar radiation to energy, as well as innovative materials and structure to go beyond the conventional power conversion ratio. In line with these innovations, there are concerns about greenhouse gas emissions of the solar cells, materials for the solar technologies and other relevant environmental impacts of the manufacturing processes. This review is conducted on life cycle assessments of solar cells, considering the climate change and natural resource shortage context. It is identified that the majority of existing life cycle assessments on solar cells take into account four typical environmental impacts: energy consumption, greenhouse gas emissions, material depletion, and toxicity. Though the diverse methodological aspects make it difficult to directly compare these environmental impacts among various types of solar cells, the obtained results hinder that emerging solar cells such as perovskite solar cells or tandem solar cells are likely to have better environmental profiles than conventional silicon based and thin film solar cells, in terms of energy consumption, greenhouse gas emissions and material consumption. However, the emerging solar cells may utilize toxic materials in which their eco-toxicity and human toxicity should be further considered during the design of the technologies. Moreover, it is identified that the energy and environmental hotspot lies in the manufacturing process, regardless of impact indicators and types of solar cells.

* Corresponding author.
E-mail addresses: maurizio.cellura@unipa.it (M. Cellura), lequyen.luu@unipa.it (L.Q. Luu), francesco.guarino@unipa.it (F. Guarino), sonia.longo@unipa.it (S. Longo).

https://doi.org/10.1016/j.scitotenv.2023.168019
Received 7 September 2023; Received in revised form 19 October 2023; Accepted 20 October 2023
Available online 23 October 2023

1. Introduction

The global solar installation capacity increased from 716 GW in 2020 to 849 GW in 2021 (IRENA, 2022). More than half of the solar installation capacity was located in Asia, with 485 GW, followed by Europe (EU), with 160 GW of solar installation in 2021 for the 27 state members of the European Union and 185 GW for the whole region. Among EU-27 countries, the top three countries with the highest solar installation are Germany, Italy and Spain. The International Energy Agency (IEA) forecasted an average annual solar generation growth of 25 % in the period 2022–2030 (IEA, 2020). With the increase in solar installation capacity, it is expected that more resources are required for solar technologies. These resources are not only related to energy consumption for manufacturing solar technologies but also related to the use of materials whether they are abundant or scarce, if they cause any toxicity to the ecosystem or human health.

In the context of climate change and material shortage, it is essential to develop innovative solar technologies which are more resource efficient and cause less negative environmental impacts. For example heterojunction thin film solar cells to reduce manufacturing costs and be able to be integrated into buildings. Another example is tandem solar cells based on gallium, silicon or perovskite with high efficiency (Allouhi et al., 2022). At the same time, these technologies need to be developed with the application of eco-design, which integrates the environmental aspects into the product development process by balancing ecological and economic requirements (Delaney et al., 2022). The eco-design of these innovative solar technologies should be considered under the life cycle thinking perspective, in other words, minimizing their negative environmental impacts in all stages of the technologies' life cycle. Through the application of eco-design, the quality of the technologies is maintained according to their ideal usage, meanwhile having competitive fabrication cost, using available and non-toxic materials, and causing the least environmental impacts.

Solar technologies have a long history, with the first solar cooker being invented in the 17th century, the first solar collector being invented at the beginning of the 18th century, and the first solar cells being invented the end of the same century (DOE, n.d.). Similarly, the life cycle thinking perspective, and one of its relevant method - life cycle assessment (LCA) is well-developed, with the first international standard on conducting an LCA being published in 1996. These two topics, consequently, appeared intensively in the literature. The initial search on the Science Direct database for LCA and solar cells returned nearly 5000 reviews by April 2023. Although the huge number of review literatures, there is no systematic and statistical review on the life cycle environmental impacts of emerging solar cells, in the context of climate change and material shortage.

To the best of the authors' knowledge, there are six reviews simultaneously covering both topics of LCA and solar cells. As early as 2010, Sherwani et al. conducted a review on LCA of silicon based solar cells (SSC) such as amorphous (a-Si), mono-crystalline (mono-Si) and multi-crystalline (multi-Si) solar modules (Sherwani and Usmani, 2010). The review covered from cradle to gate with two indicators of mass and energy flows. The product systems were extended in Peng et al. (2013) to examine two more types of PV modules, including CdTe thin film (CdTe) and CIS thin film (CIS). This review covered two indicators of energy payback time (EPBT) and life cycle greenhouse gas (GHG) emissions (Peng et al., 2013). Tripathy et al. conducted a review with the same indicators as Peng et al.'s study, but on building integrated PV (BIPV) applied on roofs, façades and skylights (Tripathy et al., 2016). Similarly Ludin et al. compared different solar PV technologies of SSCs, thin-film solar cells (TFSCs), dye sensitized solar cells (DSSCs), perovskite solar cells (PSCs), quantum dot sensitized solar cells (QDSSCs) in terms of cumulative energy demand (CED), EPBT and GHG emissions (Ludin et al., 2018). It can be observed that before 2018, the existing reviews concentrated on two environmental indicators related to energy and climate change. Moreover, the studied product systems have gradually developed from conventional, crystalline SSCs into TFSCs and PSCs.

Later on, the reviews of Gressler et al. (2022) and Muteri et al. (2020) provided information on other environmental impacts. While Gressler et al. compared different materials and hotspots for organic solar cells (OSCs), DSSCs, PSCs, and QDSSCs over the life cycle of the technologies (Gressler et al., 2022); Muteri et al. analysed the energy and environmental impacts, hotspots of three generations of grid connected PV (Muteri et al., 2020). Though these two reviews are very close to the topics of this current review, unfortunately they did not provide any statistical value on life cycle environmental impacts and hotspots of the solar technologies.

The objective of this review paper is to provide a critical environmental assessment of the emerging solar technologies, applying life cycling thinking and in the context of climate change and material shortage. The paper lists materials and design of solar technologies, with some recent advancements. Besides, it identifies the current research trends on solar technologies, and reports some key environmental impacts and hot spots during the life cycle of the emerging solar technologies. All this information is useful for the eco-design of emerging solar technologies, which will be useful for not only energy and environment engineers, but also policy makers, who want to develop the solar cells with higher efficiency and better environmental profile.

2. Materials and methods

The review is a systematic review of LCA studies, which was conducted in five steps, as follows: (1) formulating research questions; (2) searching relevant studies; (3) appraising the quality and extracting data; (4) synthesizing and (5) interpreting (Glasziou, 2013). The logical flow of developing this review paper is presented in Fig. 1. At the same time, the review follows the guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2000 for searching, screening and selecting the reviewed articles and statistically analysing the articles' obtained results (Page et al., 2021a; Page et al., 2021b). The PRISMA flow of identification, screening and inclusion of the reviewed articles is presented in Fig. SI1. For analysing methodological aspects such as product systems, system boundaries, functional units and impact categories of LCA studies, the review referred to the framework for conducting systematic literature review for life cycle thinking studies (Gulotta et al., 2023).

Firstly, the research questions of this review paper are formulated by checking the existing reviews on the same topics of LCA and solar cells. Three research questions have been identified, including:

- What are the materials and structure of solar cells, especially emerging solar cells?
- What are the main life cycle environmental impacts of the emerging solar cells, with statistical value?
- What are the environmental hotspots of the life cycle of the emerging solar cells?

Secondly, the keywords and timeframe for searching for relevant studies are defined. Three keywords related to the research topic have been used, including LCA, solar cells and solar coatings. The keywords "solar cells" and "solar coatings", instead of generic keywords such as solar PV technologies, solar thermal technologies, etc., are used to focus on the 'material' scale of solar systems. The search strings of ("solar coatings" OR "solar cells") AND "life cycle assessment" have been applied on the Science Direct database (*Science Direct Database*, n.d.), which returned 5518 studies being published from 2000 to 2023. The Science Direct database is selected because it is evaluated to be a suitable database for systematic review and meta-analysis (Gusenbauer and Haddaway, 2020), with more than 2650 journals and 43 thousand e-books (*Science Direct Database*, n.d.). The publication timeframe is narrowed from 2017 to 2023 due to two reasons. First, the recent timeframe

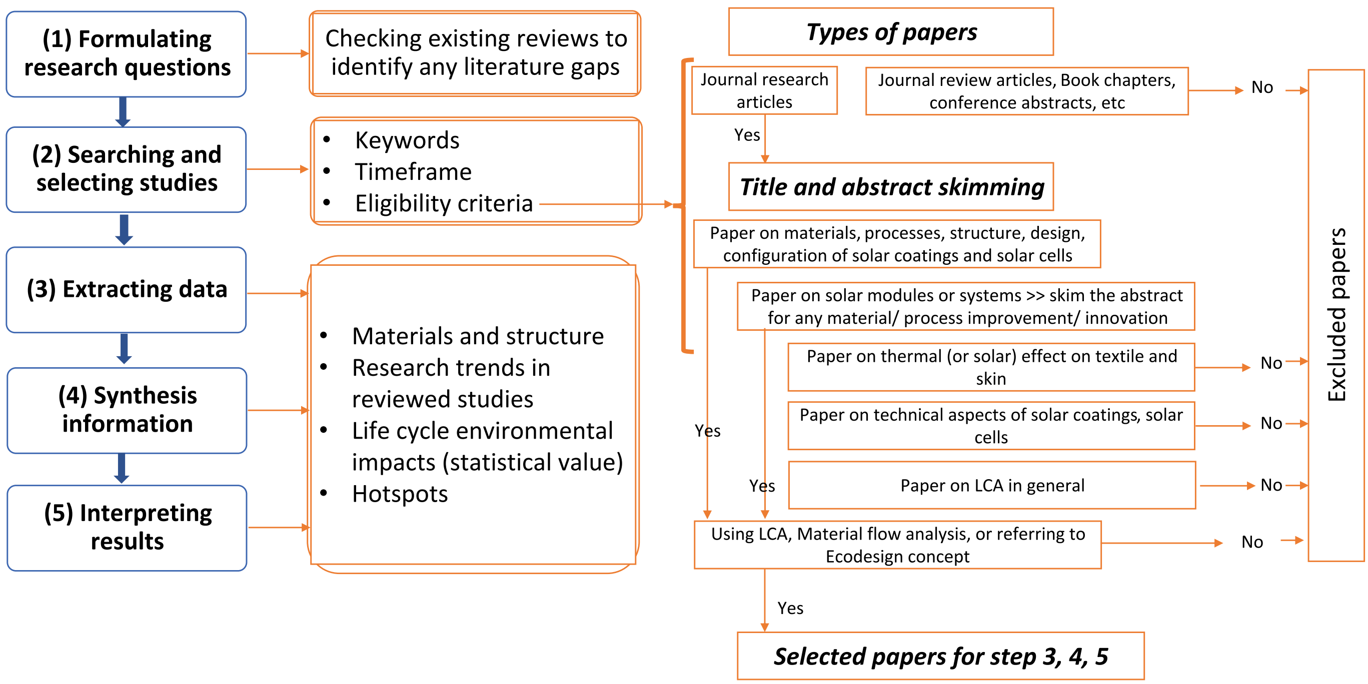


Fig. 1. Logical flow within the review development.

helps to narrow the publications on the "emerging" technologies with improved efficiency, innovative materials, etc. Secondly, because the previous review of Muteri et al. (2020) selected articles being published till 2018, the timeframe from 2017 to 2023 will avoid duplicating the effort of the previous review.

Furthermore, the searched studies are screened and selected based on the three following criteria:

- journal research articles,
- skimming the titles to include studies on materials and structure (layers, configurations, design, etc.) of solar cells (or coatings), and
- screening the abstracts for LCA (or life cycle concepts).

At the end of the skimming and screening process, 24 papers on solar cells, solar coatings and LCA are selected for extracting data. Finally, the extracted data on materials, structure, environmental impacts and hotspots of emerging solar cells will be synthesized and interpreted, as mentioned in steps (4) and (5).

3. Solar technologies

Solar cell is the backbone of solar energy technologies, which converts solar radiation into power. Solar cells are generally classified into three main types of the first generation (crystalline silicon based solar cells), the second generation (thin-film solar cells) and the third generation (non-silicon based solar cells such as organic solar cells, dye sensitized solar cells, etc. (Muteri et al., 2020). Though this classification is popular and convenient, in the past, it discriminated the conventional silicon based solar cells and thin-film solar cells, in which the latter was deemed to be the next generation. However, with the improvement in silicon materials, the cost of silicon based solar cells reduces and their efficiency increases. Recently, many 'third generation' solar cells are silicon based, for example the combination of silicon and perovskite in tandem solar cells. Therefore, instead of describing the solar technologies by the generations, this section will present different solar technologies based on the materials and structure of the solar cells, with some discussion on the improvement in their efficiency and the change in their market share.

3.1. Materials for solar cells

Based on the materials for solar cells, there will be two main categories of materials, silicon based and other non-silicon materials. Most of the existing commercial solar cells are based on silicon (Jungbluth et al., 2012). The silicon based solar cells include mono-Si, multi-Si, ribbon silicon (ribbon-Si) (panel) and a-Si (thin film). Other materials for exploiting solar energy are cadmium telluride (CdTe), copper indium gallium selenide (CIGS), copper indium diselenide (CIS), indium phosphide (InP), photosensitive materials such as titanium dioxide (TiO2), or gallium arsenide (GaAs). Recently, perovskite has been researched as a potential material in the solar energy sector. The classification of solar cells by materials and architecture are summarized in Table 1.

Most of today's solar PV cells are mono-Si and multi-Si, accounting for approximately 80–90 % of the total solar photovoltaic cell market (Jungbluth et al., 2012; Li et al., 2018; IEA, 2022). As of 2008, the shares of commercial solar cells are 51 % of multi-Si, 37 % of mono-Si, 5 % of a-Si, and 1.5 % of ribbon-Si technology (Jungbluth et al., 2012). These shares have recently changed with the decrease of multi-Si to 15 %, and

Table 1
Classification of solar cells by materials and Structure.

Material structure	Silicon (95 % of the market)	Non-silicon (5 % of the market)
Conventional (single junction, mono facial)	Mono-Si Multi-Si (dead) Ribbon-Si (never born)	
Passivated	PERC (86–88 % of the market)	
Bi-faciality and passivated	PERC bi-faciality	
Thin-film (heterojunction)	a-Si	CdTe (going to finish) CIGS/CIS (going to finish) GaAs (space application) Perovskite (lab scale)
Bi-faciality and heterojunction	Silicon based bi-faciality heterojunction	
Tandem (multijunction)	Silicon based tandem	CIGS based tandem Perovskite based tandem (Maybe in future)

the increase of mono-Si to 80 % of the market (IEA, 2022). Materials for the crystalline silicon cells are abundant, and their efficiencies are high, up to 26.1 % (Allouhi et al., 2022), which explains for their large and increasing share of the market. Meanwhile, solar cells based on other materials accounted for a small percentage, with 5 % CdTe thin film technology, and 0.5 % other thin film technologies (Jungbluth et al., 2012). This small share may originate from the concern on raw material availability, hazardous environmental issues related to the materials used, and storage systems (Allouhi et al., 2022).

3.2. Structure of solar cells

The existing SSCs are frequently structured into passivated emitter and rear contact (PERC) cells. By integrating a passivated oxide layer on the back of the cells, the electron recombination reduces, and the capacity of light absorption and the internal reflectivity increase. Consequently, the efficiency of cells improves, for example by about 0.8 % to 1 % points in mono-Si cells and 0.4 % to 0.8 % points in multi-Si (IRENA, 2019). Another way to increase the efficiency of the mono facial traditional cells is converting into bi-facial. The bifacial cells are designed to collect energy from both sides of the cells. It is normally known as the combination of PERC and SSC (PERC bi-faciality). The efficiency of the PERC bi-faciality cells may be up to 25 % (Vodapally and Ali, 2022). See Fig. 2 for different layers and relevant materials of the solar cells.

Thin-film cells are manufactured with semiconducting materials, which allows producing solar cells at only a few micrometres thick (IRENA, 2019). They used to have lower efficiency than crystalline solar cells, but the situation has changed recently. CdTe and CIGS cells have achieved an efficiency of around 21 % and 22.9 %, respectively (IRENA, 2019; Philipps et al., 2023). GaAs cells also have a very high efficiency, from 25 % to 30 % (IEA, 2022). It should be noted that all these above mentioned thin-film cells are based on rare materials, such as indium for CIGS or gallium arsenide and germanium for GaAS cells. The newly introduced material, perovskite is promising with laboratory-scale efficiency of 23.3 % (Allouhi et al., 2022), or even up to 24.2 % in US and Korean labs - close to silicon's lab record of 26.7 % (IRENA, 2019). There are some concerns on its consumption, and consequently leaching of toxic material, e.g. lead (Kwak et al., 2020); and the requirement of encapsulation, for example an aluminium oxide layer or a seal glass or PET plates to protect the easily dissolvable crystals from humidity and moisture (IRENA, 2019).

In order to further increase the efficiency of the cells, approaching or even above the Shockley–Queisser limit of 30 % for single junction solar cells (Vodapally and Ali, 2022), the tandem structure has been studied based on multi junction. Basically, tandem solar cells are made up of several layers of cells, in which each layer of cells absorbs and converts a specific light band into electricity (IRENA, 2019). Materials of tandem cells are diverse, either based on silicon or non-silicon materials. Currently, there are several combinations of perovskite and CIGS, perovskite and silicon (Hosseinian Ahangharnejhad et al., 2020). The most updated laboratory record of tandem cell efficiency is at 33.7 % for perovskite and silicon tandem solar cells (NREL, 2023). The efficiency of tandem cells is expected to increase to 46 % (IRENA, 2019). However, the commercialization of these cells has been limited by the high cost of the materials and manufacturing processes (IRENA, 2019; Hosseinian Ahangharnejhad et al., 2020).

4. Life cycle assessment

This section presents the results of the review, including the methodological aspects such as year of publication, product system, functional unit, system boundary and environmental indicators; and the statistical analysis of some environmental impacts of solar technologies such as energy related indicators, GHG emissions, material consumption, and toxicity.

4.1. Current research trends

Apart from conventional material, e.g. silicon, the current research conveys new materials for solar cells such as luminescent and organic materials. Considering 24 reviewed case studies, there was an identified trend on the materials of the solar cells. PSCs attracted a lot of the attention due to their potentially high power conversion efficiency. This was presented by the fact that nearly half of the reviewed case studies were on PSCs (ten case studies). At the same time, the other half of the reviewed case studies concentrated on silicon (Si) based solar cells (11 case studies). The remaining case studies either focused other types of conventional materials of the thin film solar cells such as CdTe (three case studies) and CIGS (one case study), or the introduction of new materials such as organic solar cells (OSCs), luminescent solar cells (LSCs).

Considering the structure of the cells, apart from the conventional structure of single junction and mono-facial that are frequently observed in SSCs, some new structure has been proposed such as tandem solar cells (three case studies) and bifacial solar cells (two case studies).

The system boundaries were diverse, with cradle to gate, gate to grave, and cradle to grave. The cradle to gate system boundary was applied in eight case studies; two case studies applied gate to gate, focusing on the manufacturing process and one case study covers from cradle to end of use. The small number of cradle to end of use studies can be explained by the fact that the impact of using the solar cells is not much compared to the whole life cycle impact. Six of these case studies are on the innovative solar cells such as PSC and OSC. This is understandable as the PSC and OSC are emerging solar technologies, some of them are uncommercialized and still at lab-scale. Consequentially, the manufacturing stage in general and the industrial production of these solar cells attracted more attention. At the same time, at this stage of research, development and innovation, there is an opportunity to improve the cell performance while reducing its negative environmental impacts and material consumption by integrating eco-design. The cradle to grave system boundary was used in eight case studies. These studies are either on the conventional solar cells or emerging solar cells, but the difference is not much with five case studies on SSCs, four case studies on PSCs and two case studies on tandem solar cells.

The end of life stage has limited application, with four case studies on gate to grave (waste treatment), and one case study applied both gate to cradle (recycling and reuse materials) and gate to grave, from 2019 to 2022. The solar power started to bloom at the end of the 2010s; and considering that the average lifetime of solar panel is from 25 to 30 years, it should be the time to prepare for the end of life of the cells. Some end of life treatments were studied, including recycling and treatment of waste from decommissioned solar cells, in context of shortage of materials, as well as preventing the potential risk of leaking of toxic materials from decommissioned solar cells into the environment.

The functional units (FUs) used in the reviewed case studies are diverse with m^2 of cells, kWh of electricity, kg of cells/materials, m^3 of coating. Among these FUs, the most popular FUs were m^2 of cells (nine case studies) and kWh of electricity (seven case studies), while kg and cell/module are less common, being applied in three case studies each. The FUs of m^2 and kWh are popular, as they are directly related to the technical characteristics of the cells. The FU of m^2 of the cell are relevant to the environmental impacts of the cells, lamination or modules; and the life cycle inventory databases frequently report per unit area (m^2) (Frischknecht et al., 2020). Meanwhile the FU of kWh of electricity which is relevant to the cells' efficiency and their actual deployment, is recommended for conducting an LCA on solar PV by IEA's LCA method guidelines (Frischknecht et al., 2016), as well as the ongoing European Commission's guideline on Product Environmental Footprint of energy production and transmission (EC, n.d.; EC, 2021). As this review paper concerns different types of solar cells, the results of the case studies reviewed which were calculated per m^2 of cells will be converted into

Conventional SSC	
Electrode/ grid contact	Ag
Anti-reflective coating	Al2O3/ TiO2/ SiO2
Absorber/ active layer	n-p silicon wafer
Back surface field	Al
Electrode/ rear contact	Al paste

PERC	
Electrode/ grid contact	Ag
Anti-reflective coating	Al2O3/ TiO2/ SiO2
Absorber/ active layer	n-p silicon wafer
Passive layers	SiNx
Back surface field	Al2O3
Electrode/ rear contact	Al paste

PERC bi-ficial cells	
Electrode/ grid contact	Ag
Anti-reflective coating	Al2O3/ TiO2/ SiO2
Absorber/ active layer	n-p silicon wafer
Back surface field	Al
Anti-reflective coating	Al2O3/ TiO2/ SiO2
Electrode/ rear contact	Al paste

PSC	
Electrode/ grid contact	Ag
Transparent conductive layer	Indium Tin Oxide
Electron transport layer	ZnO/SnO2
Absorber/ active layer	Perovskite
Hole transport layer	Cu2O/ SpiroMeOTAD
Electrode/ rear contact	Al, Ag, Au

Tandem solar cells	
Lamination	PET
Electrode/ grid contact	Ag
Hole transporting layer	PTAA, MeO-2PACz
Electron transport layer	BCP/ PCBM
Absorber/ active layer	Perovskite
Hole transport layer	PTAA, MeO-2PACz
Electron transport layer	BCP/ PCBM
Absorber/ active layer	Silicon/ Perovskite
Hole transport layer	PTAA, MeO-2PACz
Electrode/ rear contact	Ag, Au
Encapsulation	PET

Heterojunction bi-facial cells	
Electrode/ grid contact	Ag
Transparent conductive layer	Indium Tin Oxide
Absorber/ active layer	p-i-n-i-n silicon
Transparent conductive layer	Indium Tin Oxide
Electrode/ rear contact	Ag

Color explaination
Lamination/ Encapsulation
Electrode/ Grid contact/ Rear contact/ Back surface field
Anti-reflective coating
Transparent conductive layer
Hole transporting layer
Electron transport layer
Absorber/ Active layer
Passive layers

Fig. 2. Layers and materials of various solar PV cells.

environmental impacts per kWh of electricity, following the equation of Celik et al. (2016):

$$Impact_{kWh} = \frac{Impact_{m^2}}{I \times \mu \times PR \times LT} \tag{1}$$

in which:

$Impact_{kWh}$ is the impact per 1 kWh of electricity generated by the cells (unit of the impact/kWh)
$Impact_{m^2}$ is the impact per 1 m^2 of cell area (unit of the impact/m^2)
I is insolation constant per m^2 for a year (kWh/(m^2yr))
μ is the cell efficiency (dimensionless)
PR is the performance ratio of the cells (dimensionless)
LT is the lifetime of the cells (yr)

The current research trends on material, structure, system boundary and FU by year are illustrated in Fig. 3a.

The impact indicators studied are various, and frequently cover all environmental aspects such as global warming (GWP), eutrophication, acidification, human toxicity (HTP), ecotoxicity (ETP), ozone depletion, photochemical, particulate matter, abiotic depletion (ADP). Although the selected impact indicators are extended to economic and social indicators, for example economic benefits and human health impacts of the solar cells (human health is one of three end-point indicators including environmental impact, resource consumption and human health), the number of studies on environmental indicators outweighs the number of studies on socio-economic indicators. Fig. 3b presents methodological aspects in selecting indicators. It shows the number of case studies which were analysed and quantified various environmental and socio-economic impacts.

Among the environmental impact indicators, toxicity, including both HTP and ETP, attracted a lot of attention, with 19 out of 24 case studies. Other impacts that attract attention are energy related indicators (18 case studies), GWP (17 case studies), ADP (including material and metal consumption) (15 case studies), acidification and eutrophication (14 case studies).

Although solar energy can be exploited in the forms of photovoltaics and thermal energy, it should be noted that most of the case studies focused on solar PV. Solar thermal energy was studied in only one LCA, considering solar dryer.

The information on studied products, system boundaries, functional units and impact indicators of the case studies and summarized in Table SI1.

4.2. Energy related indicators

Some energy related indicators include such indicators as CED, Cumulative Energy Yield (CEY), Energy Return on Investment (EROI), Net energy ratio (NER), EPBT and fossil fuel depletion potential (FFDP). While the EROI and EPBT is recommended provided with detailed guidelines for calculation by IEA Task 12 on solar PV and sustainability (Frischknecht et al., 2016; Raugei et al., 2016), other indicators such as CED and FFDP are quite common in LCA studies. The use of various energy related indicators is provided in Table SI2.

CED is the amount of primary energy consumed during the life cycle of the product. There are some indicators which are similar to CED, such as total energy consumption, total energy requirement and total electricity consumption. CED is measured in MJ by applying the following equations:

$$CED = \sum A^*CF \tag{2}$$

in which:

A is the life cycle amount of different types of fuels (kg or m^3)
CF is the characterization factor of different types of fuels (MJ/kg or MJ/m^3)

In the reviewed case studies, the CED of PSC from cradle to gate ranges from 4.29E-01 to 2.13E+02 MJ per kWh, for ideal process and for lab scaled production (Alberola-Borràs et al., 2018a). The reported CED in Sánchez et al. (2019) were also in this range, at 6.70E-01 and 8.75E+00 MJ for different manufacturing processes, flash infrared annealing (FIRA) or antisolvent (Sánchez et al., 2019). The reported results for 1 m^2 were much larger, at 1.15E+02 MJ per m^2 of PSC

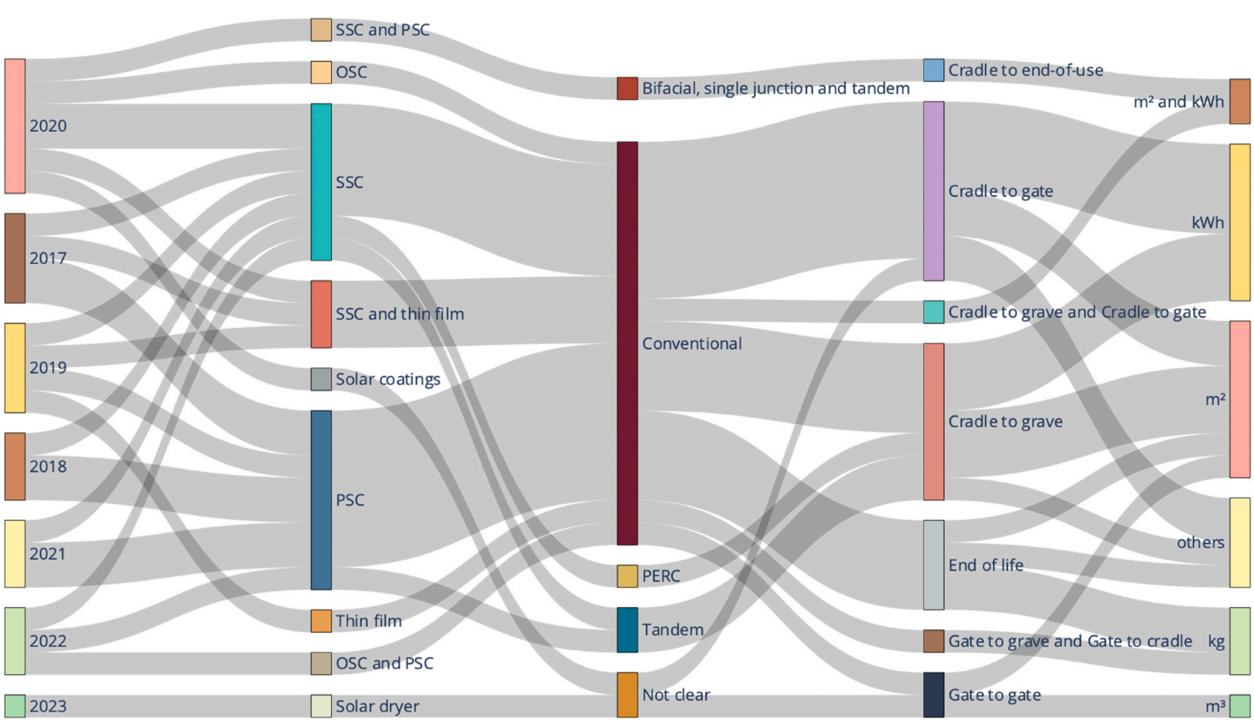


Fig. 3a. Current research trends on methodological aspects (from left to right: year, material, structure, system boundary and functional unit).

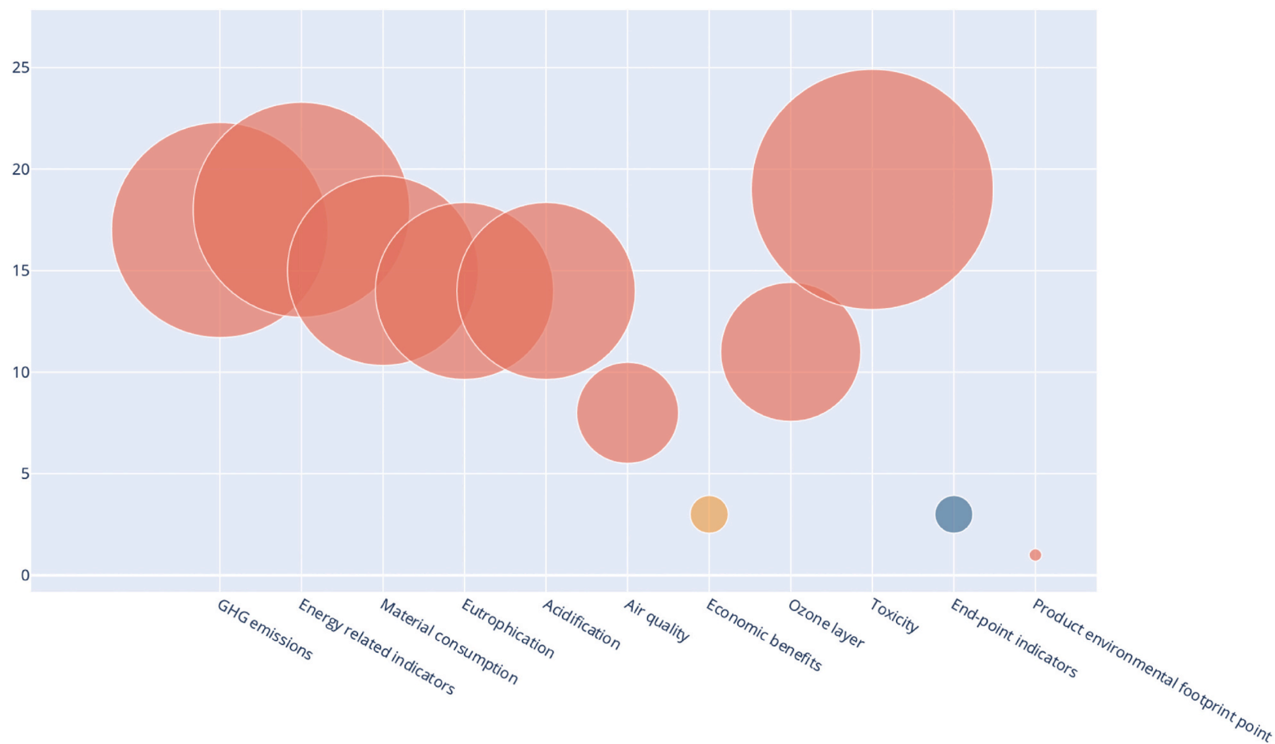


Fig. 3b. Methodological aspect in selecting life cycle impact indicators.

module (Li et al., 2022). However, when being converted into the FU of kWh, the CED reported by Li et al. (2022) dropped significantly 3.07E-02 MJ per kWh, much lower than the results of other studies.

The cradle to grave CED was 6.59E+03 to 9.32E+03 MJ per m^2 of active area of PSC (Alberola-Borràs et al., 2018b), being equivalent to 1.03E+00 to 1.46E+00 MJ per kWh. These numbers were in the range of the reported cradle to gate CED of (Alberola-Borràs et al., 2018a; Sánchez et al., 2019).

The cradle to gate CED of organic transparent PV ranged from 3.1 to 11.4 MJ per Wp, depending on materials of glass or plastics and efficiencies of the current or future technologies (Anctil et al., 2020).

While CED is used to measure the energy consumption, CEY considers the energy production. It is the amount of energy production during the life cycle of the product, presented in MJ of energy or kWh of electricity. CEY depends on the total energy output of the system, consequently on the efficiency of the module, the tilt of the cells, solar radiation, temperature in the installation site, and many other technical parameters of the system as well as the installation site (Hosseinian Ahangharnejhad et al., 2019). Though it is a 'life cycle' indicator, CEY originates from the 'use' stage of the module, in other words, generating electricity or thermal energy during the operation of the solar cells. CEY was applied by only one author, in which the CEY of solar cells ranged from 7.8 MWh to 12.6 MWh per m^2 of PV module (Hosseinian Ahangharnejhad et al., 2020).

EROI or NER is the ratio of the amount of energy delivered in relation to the amount of energy invested to explore, extract, process, produce, generate, transmit and transport it (Raugei et al., 2016). Though these indicators are called by different names, they are the same by nature, and being calculated by applying Eq. (3). These two indicators are dimensionless. EROI was applied in Jia et al.'s study, which is 9.4 to 13.17 for SSCs (Jia et al., 2021). NER indicator was applied in Rao et al.'s study for PSCs, which is calculated at 3.08 (Ramamurthy Rao et al., 2021). Both studies of Jia et al. and Rao et al. covered the system boundary from cradle to grave, meaning that they include energy production and consumption from the material extraction to end of life of the product system. The Eq. (2) is presented as followings:

$$EROI = \frac{Energy_{out}}{Energy_{in}} \quad (3)$$

in which:

$Energy_{out}$ is the amount of energy generated (MJ or kWh)
$Energy_{in}$ is the amount of energy used in the processes along the life cycle (MJ or kWh)

EPBT is the amount of time it takes for an energy system to generate the amount of energy equivalent to the amount that took to produce the system (Frischknecht et al., 2016). The EPBT of PSC is 2.17 years considering cradle to gate (Okoroafor et al., 2022), and 1.41 to 2.12 considering gate to gate system boundary (Correa Guerrero et al., 2021). The EPBT of PSC reduces to 0.97 years (Ramamurthy Rao et al., 2021), when the system boundary is extended to cover the whole life cycle of the cells, e.g. from cradle to grave. For CdTe module, the cradle to grave EPBT is around 1.3 and 1.34 years, depending on whether recycling is applied in the end of life treatment of the product (Vellini et al., 2017). The cradle to grave EPBT of Si module is 2.6 years, but may be reduced to 1.6 years if recycling is applied (Vellini et al., 2017).

Fossil fuel depletion is a life cycle environmental impact indicator being similar to CED, but it only limits to fossil energy sources. The fossil fuel depletion of different types of solar cells is converted into the FU of kWh and presented in Table 2.

The cradle to gate fossil fuel depletion of SSC was from 7.83E+00 to 1.54E+01 g oil eq per kWh of electricity depending on type of solar cells, mono or multi crystalline (Stamford and Azapagic, 2019), and 1.44 MJ surplus per kg of c-Si, being equivalent to 6.05E+00 kg oil eq per kg c-Si (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020). The cradle to end use resource depletion of SSC was 1.98E+02 MJ per m^2 PV module (Hosseinian Ahangharnejhad et al., 2020). The end of life fossil fuel depletion of SSC was 8.11E+00 kg oil eq per m^2 of end of life PV panel treated (Corcelli et al., 2018). Meanwhile, the end of life treatment of SSCs was from 4.00E-01 to 1.48E+00 kg oil eq per kg of PV material depending on end-of life treatment (Contreras Lisperguer et al., 2020).

Table 2
Fossil fuel depletion of SSC, thin film and PSC (MJ per kWh).

Product system	System boundary	Fossil fuel depletion	Notes
SSC	End of life	6.65E-02	c-Si PV panel
Thin film	Cradle to gate	1.97E-01	CIGS PV, Spain
Thin film	Cradle to gate	3.38E-01	CIGS PV, UK
Thin film	Cradle to gate	2.44E-01	CdTe, Spain
Thin film	Cradle to gate	4.18E-01	CdTe, UK
SSC	Cradle to gate	3.28E-01	Multi Si, Spain
SSC	Cradle to gate	5.65E-01	Multi Si, UK
SSC	Cradle to gate	3.74E-01	Mono Si, Spain
SSC	Cradle to gate	6.44E-01	Mono Si, UK
PSC	Cradle to gate	2.11E-02	psc, conventional
PSC	Cradle to gate	8.15E-03	psc, low energy transfer
OSC	Cradle to gate	2.49E-02	osc, conventional
OSC	Cradle to gate	1.04E-02	osc, low energy transfer
PSC	Cradle to gate	6.14E-01	psc, inkjet printing

The grave to gate resources depletion of SSC was 7.1E-01 MJ surplus per kg c-Si (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020), being equivalent to 4.42E+00 kg oil eq per kg of c-Si. MJ surplus presents the additional amount of energy needed to extract one unit of fossil fuel in the future.

Regarding thin film solar cells, the cradle to gate fossil fuel depletion of CIGS was from 4.71E+00 to 8.09E+00 g oil eq per kWh (Stamford and Azapagic, 2019), which was similar to that of CdTe, from 5.82E+00 to 1.00E+01 g oil eq per kWh (Stamford and Azapagic, 2019). The cradle to grave fossil fuel depletion of CdTe was 1.80E-01 kg oil eq per kg of PV material (Contreras Lisperguer et al., 2020).

For PSC manufactured with inkjet printing method, the cradle to gate fossil fuel depletion was 6.14E-01 MJ. These numbers were at 1.47E-02 kg oil eq per kWh of electricity (Okoroafor et al., 2022), and at 3.05E+01 MJ, or 7.29E-01 kg oil eq per m^2 of PSC with graphene electrode manufactured with low energy transfer production method, and at 7.92E+01 MJ, or 1.89E+00 kg oil eq per m^2 of cell with graphene electrode manufactured with common production method (Li et al., 2022). The results of (Li et al., 2022) are much lower than that of (Okoroafor et al., 2022), when using the same FU of kWh (see Fig. 4). Cradle to end of use resources depletion of PSC ranged from 3.96E+01 to 1.98E+02 MJ per m^2 module, or 5.01E-03 to 1.10E-02 MJ per kWh of electricity, depending on types of cells (mono facial or bi-facial PSC, mono facial or bi-facial tandem PSC). The lowest was that of mono facial, followed by bi-facial, and mono facial tandem. The highest fossil fuel resource consumption is that of tandem bifacial PSC (Hosseinian Ahangharnejhad et al., 2020). Only one study reported the cradle to gate fossil fuel depletion of OSC, from 2.02E+00 to 8.43E-01 kg oil eq per m^2, or from 1.04E-02 to 2.40E-02 MJ per kWh (Li et al., 2022).

4.3. GHG emissions

The GHG emissions range significantly, due to the types of cells, the selected FUs and system boundaries of the case studies (Refer to Table SI3). For the same types of solar cells, the results per different FUs are diverse. For example, the cradle to grave GHG emissions of PSC per m^2 of active area ranged from 3.59E+02 to 6.72E+02 $kgCO_2eq$ (Alberola-Borràs et al., 2018b; Zhang et al., 2017) depending on PSC devices and end of life treatments. Meanwhile per kWh, the cradle to grave GHG emissions of this type of solar cell were much smaller 1.82E-01 to 6.78 $kgCO_2eq$ per kWh (Ramamurthy Rao et al., 2021; Zhang et al., 2017). Fig. 4 presents the GHG emissions of different types of solar cells per kWh for a better comparison.

Considering the same FUs, the range is still large among different types of solar cells. For SSCs, the cradle to grave emissions ranged from 1.84E-02 to 2.60E-02 $kgCO_2eq$ per kWh (Jia et al., 2021; Lunardi et al., 2019). The emissions were lowest for bifacial SSCs, from 1.84E-02 to 2.00E-02 $kgCO_2eq$ per kWh in (Jia et al., 2021), up to 2.60E-02 $kgCO_2eq$ per kWh in (Lunardi et al., 2019). The mono facial SSCs' emissions ranged from 2.56E-02 to 2.60E-02 $kgCO_2eq$ per kWh (Jia et al., 2021).

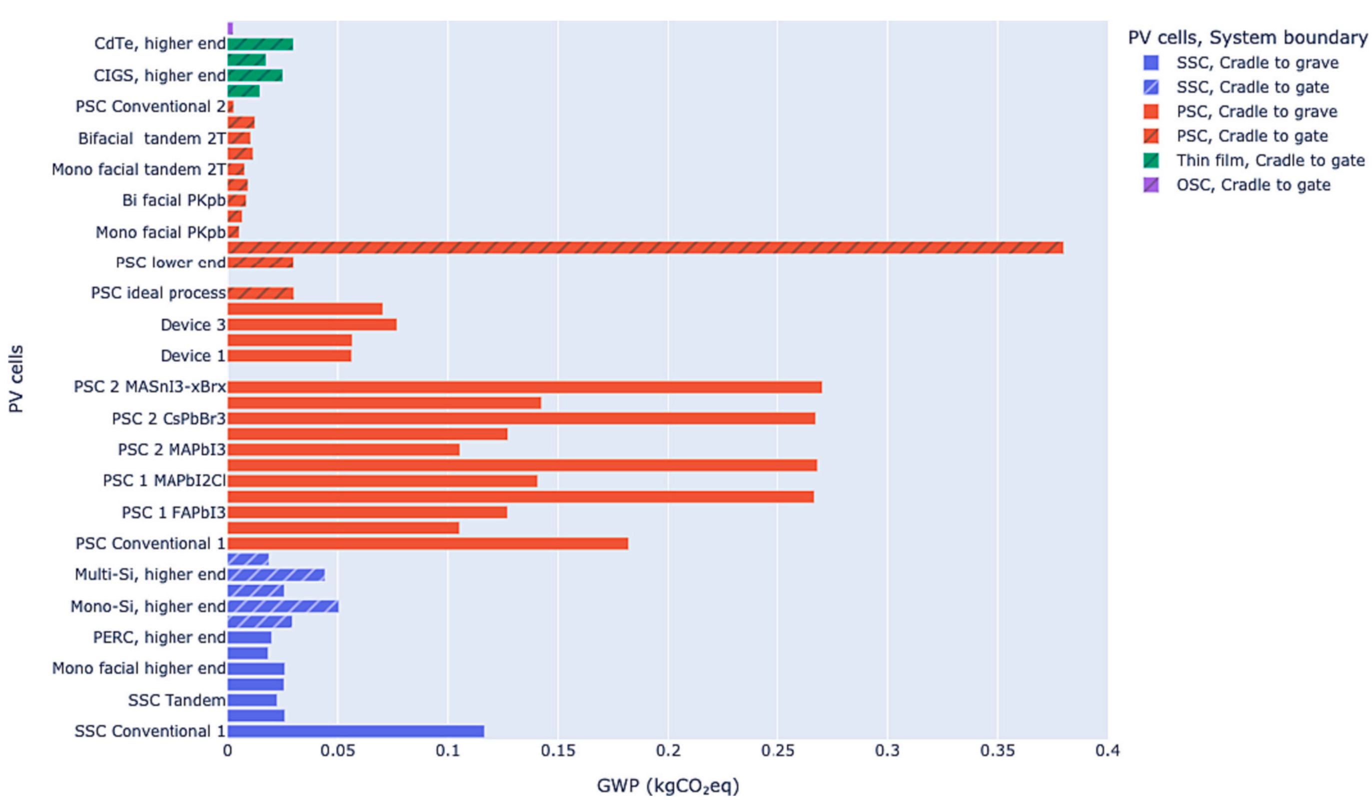


Fig. 4. GHG emissions of Si solar cells and PSC per kWh ($kgCO_2eq$).

The life cycle emissions from manufacturing process accounted for a significant part of the whole life cycle emission, which ranged from 2.57E-02 to 5.05E-02 $kgCO_2eq$ per kWh (Stamford and Azapagic, 2019). The high range of 4.42E-02 to 5.05E-02 $kgCO_2eq$ per kWh for multi and mono SSCs lies in SSCs installed in low radiation areas, for example UK (Stamford and Azapagic, 2019). It should be noted that the results of Bogacka et al.'s study did not fall within the range, and being higher, at 1.17E-01 $kgCO_2eq$ per kWh (Bogacka et al., 2017), because this number indicated the highest avoided emissions by substituting the standard energy mix of either Poland, France or Norway with energy generated from SSC with recycled materials.

The emissions of tandem SSC fall within the range of SSCs, at 2.25E-02 $kgCO_2eq$ per kWh for cradle to grave emissions of LSC-Si devices (Lunardi et al., 2019). For non-silicon, thin film solar cells, such as CIGS and CdTe, the life cycle emissions are a bit lower, ranging from 1.46E-02 to 2.50E-02 $kgCO_2eq$ per kWh for CIGS cradle to gate emissions and 1.74E-02 to 2.98E-02 $kgCO_2eq$ per kWh for CdTe cradle to gate emissions (Stamford and Azapagic, 2019).

For PSC, the cradle to grave GHG emissions ranged from 1.82E-01 to 6.78 $kgCO_2eq$ per kWh (Ramamurthy Rao et al., 2021; Zhang et al., 2017). The range is quite large due to different end of life treatments of the cells. At the same time, the higher end of PSC was reported by (Zhang et al., 2017), who quantified the environmental impacts per kWh with the assumption of one year lifetime. The cradle to gate GHG emissions of this type of solar cells were between 3.01E-02 to 9.50 $kgCO_2eq$ per kWh (Alberola-Borràs et al., 2018a; Sánchez et al., 2019). This significant difference can be explained by the manufacturing processes and scale of production.

Per m^2 of PV module, the results in cradle to gate emissions are diverse, from 4.17E+01 to 5.22E+01 in mono facial PSC, 7.45E+01 to 8.34E+01 in bifacial PSC, 7.60E+01 to 1.24E+02 in mono facial tandem PSC, and from 1.07E+02 to 1.56E+02 in bifacial tandem PSC (Hosseinian Ahangharnejhad et al., 2020). The emissions may be up to 9.4 $kgCO_2eq$ per m^2 of PV module (Li et al., 2022). Even the higher end of the PSC's GHG emissions is lower than that of OSC, at 9.5 $kgCO_2eq$ per m^2 of PV module (Li et al., 2022); and much lower than that of SSC, at 1.49E+02 $kgCO_2eq$ per m^2 of PV module (Hosseinian Ahangharnejhad et al., 2020). As mentioned above, the FU of m^2 will be converted into kWh, for statistical analysis. In this case, the cradle to gate emissions of PSC in (Hosseinian Ahangharnejhad et al., 2020) are in the range of 5.28E-03 to 9.27E-03 for mono facial and bi-facial PSCs, and 7.71E-03 to 1.24E-02 for mono facial and bi-facial tandem PSCs, which are the lower ends of GHG emissions of PSC in all reviewed case studies (see Fig. 4).

Per kg of PV material, the end of life emissions of Si based PVs are 1.38 and 5.39 $kgCO_2eq$, for recycling and landfill treatment, respectively (Contreras Lisperguer et al., 2020). Recycling different materials (CdTe) has reduced the end of life emissions by half, at 0.57 $kgCO_2eq$ (Contreras Lisperguer et al., 2020).

For electronic grade silicon, the cradle to gate emissions are much smaller, at 3.10E-05 to 5.25E-05 $kgCO_2eq$ per kg of c-Si, depending on input materials for manufacturing the silicon, from recycled or virgin materials (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020).

4.4. Material consumption

The material consumption is indicated by the abiotic depletion potential (ADP). This impact category measures the availability of resources including fossil fuel, metal and mineral depletion. As the fossil fuel depletion has been reported in the previous section in energy related indicators, this section only presents the metal or mineral depletion of solar cells.

Depending on the life cycle impact assessment methods, ADP is quantified in various units. For example, CML method quantifies the ADP in kg Sb eq, meaning that the consumption of all resources are normalized into antimony. ReCiPe method quantifies metal, mineral depletion and fossil fuel depletion separately, in which metal and mineral depletions are measured in kg Fe eq and kg Cu eq, respectively. The metal and mineral depletion of solar cells in kg Sb eq are presented in Fig. 5.

Per kWh of electricity, the ADP of mono facial SSC was 4.00E-04 to 4.10E-04 kg Sb eq (Jia et al., 2021), a little lower for bifacial Si solar cell was 2.60E-04 to 2.75E-04 kg Sb eq (Jia et al., 2021), and lowest for PSC. Zhang et al. (2017) reported the ADP of PSC ranged from 3.20E-05 to 1.32E-05 kg Sb eq per cm^2 of active area, depending on the input materials of the cells and end of life treatment practice, which are equivalent to 1.36E-05 to 7.23E-05 kg Sb eq per kWh. According to (Alberola-Borràs et al., 2018b; Okoroafor et al., 2022), the ADPs of PSC are lower, at 5.11E-06 and 1.76E-06 kg Sb eq per kWh, respectively. It should be noted that the case study of Okoroafor et al. (2022) was conducted within cradle to gate, while other case studies covered from cradle to grave. Therefore, it can be expected that the lower end of cradle to grave ADP of PSC should be higher than 1.76E-06 kg Sb eq per kWh.

The unit of kg Cu eq was only applied in one case study of Stamford and Azapagic (2019). In this case study, the authors reported the cradle to gate metal/mineral depletion of SSC were 6.17E-01 to 1.08E+00 g Cu eq per kWh of electricity depending on mono or multi Si solar cell. These numbers are similar to those of CdTe, at 5.94E-01 to 1.02E+00 g Cu eq per kWh; and lower than those of CIGS, at 3.31E+00 to 5.52E+00 g Cu eq per kWh (Stamford and Azapagic, 2019).

Two case studies used the unit of kg Fe eq for assessing metal/mineral depletion. Both these case studies focus on the end of life of the solar cells, but they are different in terms of system boundary and FU. While the case study of Corcelli et al. (2018) quantified the impacts from end of life impacts per m^2 of treated panel, the system boundary of Lisperguer et al.'s study (Contreras Lisperguer et al., 2020) covered from gate to grave and the impacts are calculated per kg of PV materials. According to (Corcelli et al., 2018), the metal/mineral depletion of SSC was 2.17E+00 kg Fe eq per m^2 of end-of-life PV panel treated. Meanwhile, the gate to grave metal/mineral depletion of SSC was from 1.35E+00 to 2.63E+00 kg Fe eq per kg of PV material depending on end of life treatment practice, in which recycling consumes less metal/mineral than landfill practice (Contreras Lisperguer et al., 2020). Lisperguer et al. also reported the metal depletion of recycling CdTe solar cells, which was at 2.05E-01 kg Fe eq per kg PV material (Contreras Lisperguer et al., 2020).

4.5. Toxicity

Toxicity includes the impacts on the health of species (ecotoxicity) and human (human toxicity) due to the persistence and accumulation of emissions in the environment, causing the increasing exposure of species and human to harmful substances and eventually causing the disease and death in species as well as human. Depending on environmental impact assessment methods, toxicity is measured in CTU (CTUe for ecotoxicity and CTUh for human toxicity), kg 1,4 DB eq, PAF/(m^2·day), PAF/(m^3·year), cases, DALY. Among these units, CTU and kg 1,4 DB eq are the most popular ones. CTU is used in the USETox model, which was developed by UNEP/SETAC to quantify ecotoxicity and human toxicity impacts based on the exposure, risks and impacts of thousands of chemicals in products and in environment. Meanwhile, the unit of kg 1,4 DB eq is applied in CML and ReCiPe methods to normalize the impacts of different chemicals to the reference flow of 1,4 dichlorobenzene. The following section describes the ecotoxicity and human toxicity of solar cells.

The ecotoxicity of SSCs generally lower than emerging solar cells. The cradle to grave ecotoxicity of SSC was 1.35E-05 kg 1,4 DB eq per kWh (Bogacka et al., 2017) and 4.51E-07 kg 1,4 DB eq per kWh (Corcelli et al., 2018). These numbers are even lower than the cradle to gate ecotoxicity of PSC, at 5.91E+00 to 4.23E+01 kg 1,4 DB eq per kWh (Li et al., 2022; Okoroafor et al., 2022) and that of OSC, at 4.66E+01 kg 1,4 DB eq per kWh (Li et al., 2022).

The same pattern is identified in the case of quantifying ecotoxicity

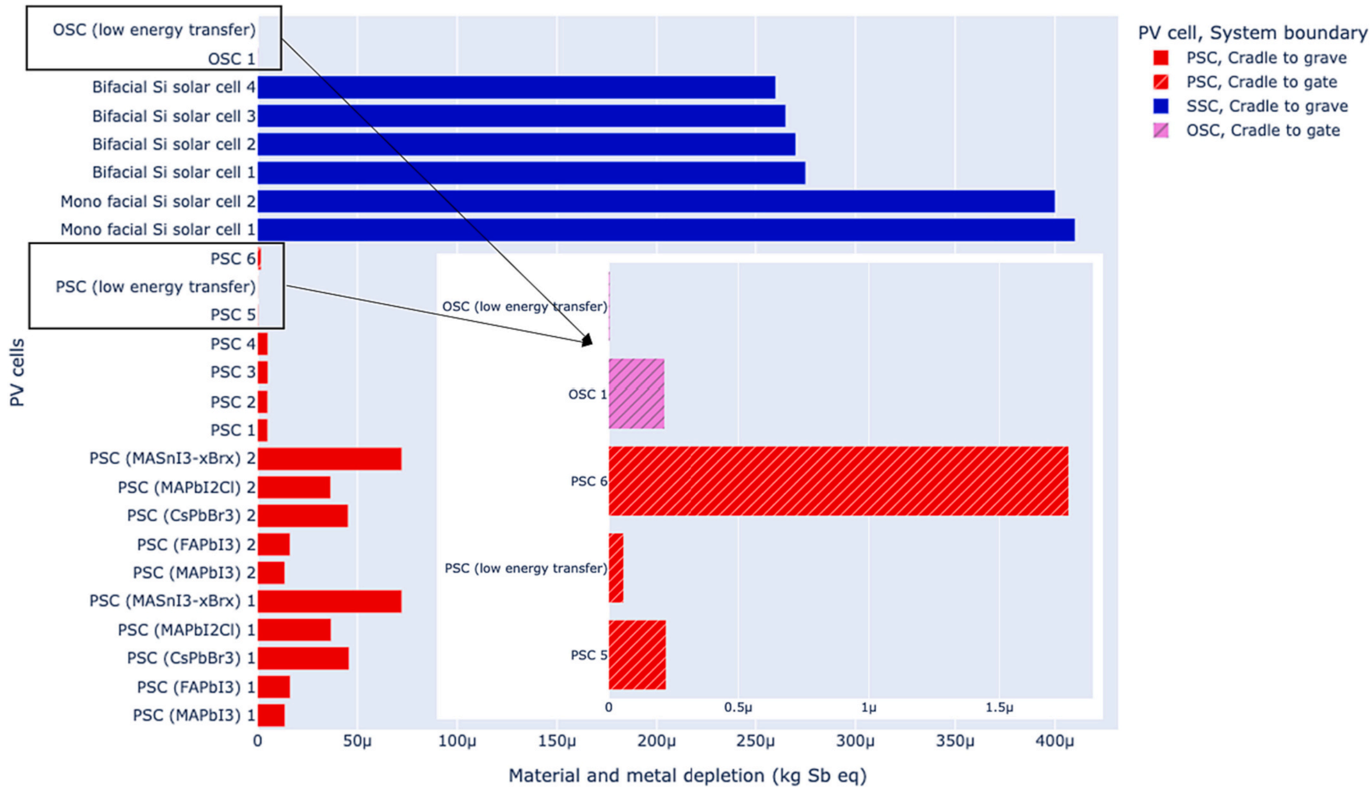


Fig. 5. Metal and mineral depletion of SSCs, thin film and PSCs per kWh.

in CTUe. The ecotoxicity of PSC ranged between 2.09E+00 to 1.37E+01 CTUe per kWh, regardless of materials for PSC and system boundary. The only exceptional is PSC in (Hosseinian Ahangharnejhad et al., 2020), which was at 3.50E-02 CTUe per kWh for mono facial and bi-facial PSC, and 6.31E-02 CTUe per kWh for mono facial and bi-facial tandem PSC. The ecotoxicity of SSCs was much lower, at 2.50E-05

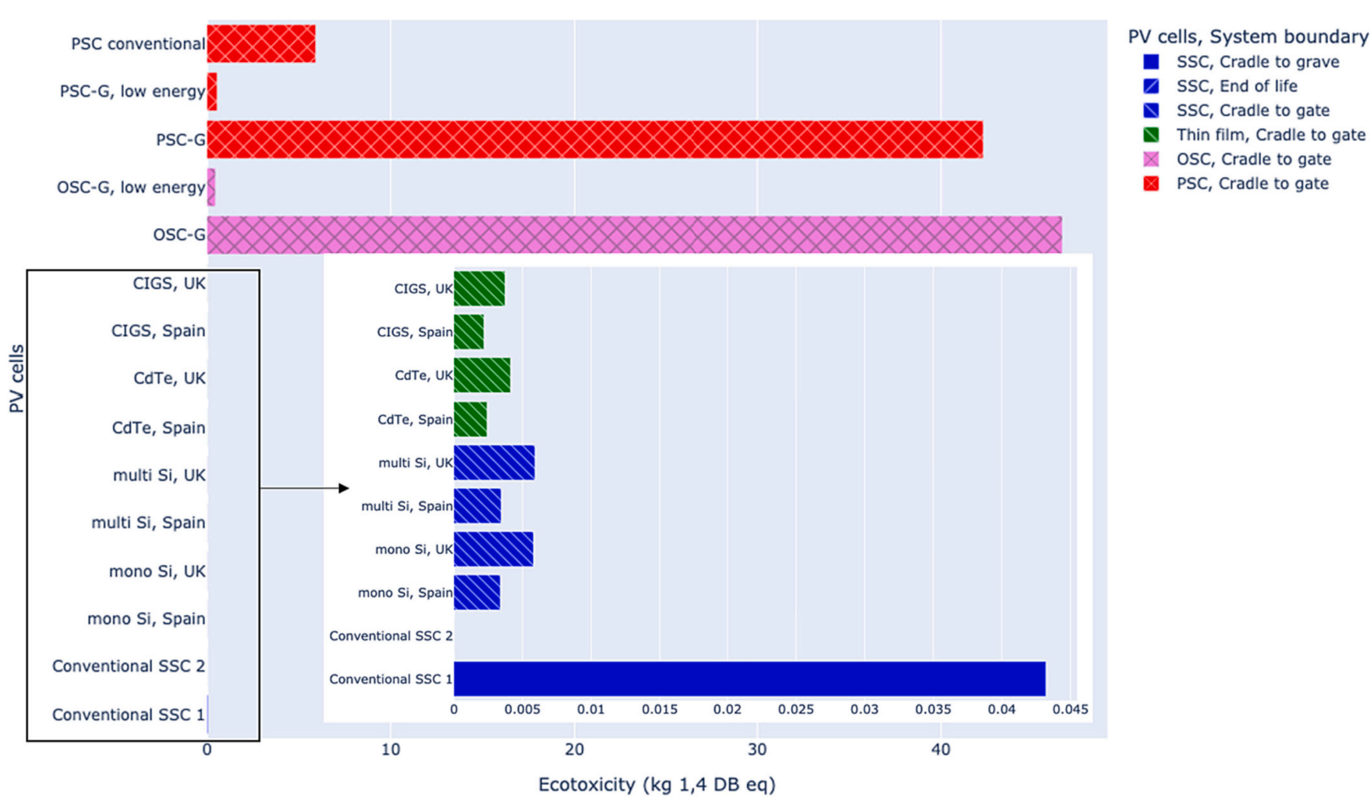


Fig. 6. Ecotoxicity of solar cells per kWh.

CTUe per kWh (Lunardi et al., 2019). The tandem SSCs had the lowest ecotoxicity, at 2.20E-05 CTUe per kWh (Lunardi et al., 2019). The ecotoxicities of solar cells are presented in Fig. 6.

With regards to human toxicity, per kWh, PERC Si device has the lowest human toxicity from cradle to grave, at 1.80E-11 CTUh per kWh (Lunardi et al., 2019), then tandem LSC-Si, at 1.00E-11 CTUh (Lunardi et al., 2019). The cradle to gate human toxicity of PSC is even higher than that of cradle to grave human toxicity of SSC, at 4.45E-09 to 1.35E-05 CTUh per kWh (Alberola-Borràs et al., 2018a) and 1.02E-08 to 1.38E-07 CTUh per kWh (Sánchez et al., 2019). However, in other studies, the human toxicity of PSC was at 1.00E-03 kg 1,4 DB eq per kWh (Okoroafor et al., 2022), which is much lower than those of Si solar cell at 7.84E-01 kg 1,4 DB eq per kWh (Bogacka et al., 2017), or CIGS at 1.47E-01 to 2.53E-01 kg 1,4 DB eq per kWh (Stamford and Azapagic, 2019). It should be noted that the human toxicity of SSC is from cradle to grave, while the reported numbers for PSC and CIGS are from cradle to gate.

The contrary results can be explained by the nature of life cycle impact assessment methods and the materials used in different types of cells. While the human toxicity which is measured in CTUh focuses on the cancer impacts of the solar cells, the human toxicity which is measured in kg 1,4 DB eq includes both cancer and non-cancer effects of the solar cells. Considering the cancer impacts, the PSCs are most lead-based, with high cancer impact factor. This causes its higher human toxicity compared to SSC which uses no (or almost no) materials that may cause cancer. In contrast, considering both cancer and non-cancer impacts, the CIGS and SSC cause high human toxicity potential, in which non-cancer impact accounts for the majority of the total impact (Stamford and Azapagic, 2019; Bogacka et al., 2017) and the cancer impact is negligible.

Human toxicity of different types of solar cells (based on materials), cradle to grave SSC was at 7.74E+00 kg 1,4 DB eq per m^2 of end-of-life PV panel treated (Corcelli et al., 2018). The cradle to gate human toxicity of OSC was from 2.32E+02 to 5.80E+00 kg 1,4 DB eq per m^2 (Li et al., 2022). The cradle to gate human toxicity of PSC was from 2.30E+02 to 3.94E+00 kg 1,4 DB eq per m^2 (Li et al., 2022), 1.00E-03 kg 1,4 DB eq per kWh (Okoroafor et al., 2022), 4.45E-09 to 1.35E-05 CTUh per kWh (Alberola-Borràs et al., 2018a), 1.02E-08 to 1.38E-07 CTUh per kWh (Sánchez et al., 2019), and 1.16E+00 DALY per kWh (Okoroafor et al., 2022). Fig. 7 illustrates the human toxicity of different solar cells.

4.6. Hotspots identification

The manufacturing stage is identified as the hotspot during the whole life cycle of the solar cells. This stage is responsible for a large share of several environmental impacts, regardless of the type of solar cells. Fig. 8a and b presents the contribution of manufacturing stages to various environmental impact indicators of PSC and SSC. In terms of GWP, the manufacturing stage accounted for 95 % to 97 % of the whole life cycle GHG emissions, depending on types of perovskite solar cells (Zhang et al., 2017). This also occurs with silicon based solar cells, and others. For example, the review in Heath et al. indicated that silicon wafers accounted for around half of the GWP (Heath, 2020). Similarly, Jia et al.'s case study identified that silicon wafers accounted for the largest share, at about 47 %–51 % of life cycle GHG emissions of mono facial and bi-facial passivated emitter rear contact (PERC) solar cells (Jia et al., 2021). For PERC with electronic grade silicon (PERC-EGS) and tandem luminescent solar concentrator - silicon (LSC-Si) solar cells, Lunardi et al. (2019) pointed out that the manufacturing stages of electronic grade silicon and mono c-Si contributed up to 70 % of the total life cycle GHG emissions.

The GHG emissions during the manufacturing stage may either come from material production (energy embodied in the materials) or the manufacturing process itself. In both cases, it obviously connects to the electricity consumption and the emission intensity of the consumed electricity. It was identified that electricity consumption has great impacts on all generations of solar cells, including crystalline silicon, thin film and organic cells. For crystalline silicon solar cells, the manufacturing and treatment of crystalline silicon are energy intensive processes (Muteri et al., 2020). For thin film and organic solar cells, though the manufacturing process requires less energy than silicon treatment, the energy embodied in the materials is the largest source of GHG emissions. Specifically, Li et al. (2022) identified that 80 % of the energy consumption of both perovskite and organic solar cells, originated from graphene transparent electrodes (GTE). Correspondingly, GHG emissions of GTE accounted for 90 % to 91 % of the GWP of both cells (Li et al., 2022).

It is the same situation for toxicity impact indicators, such as human toxicity and ecotoxicity. According to Zhang et al., the manufacturing stage accounted for 99 % to 100 % of the whole life cycle human toxicity potential of PSC (Zhang et al., 2017). Among different processes during the manufacturing stage, there is a difference in sources of human toxicity among reviewed case studies. For silicon based solar cells, both cancer and non-cancer human toxicity impacts were equally shared among the production of EGS, mono c-Si, PERC cell, module fabrication and installation (Lunardi et al., 2019). However, the study of Jia et al. indicated that the most significant human cancer impact originated from aluminium frames, followed by silicon wafers (Jia et al., 2021). The manufacturing of aluminium frames accounted for 45 % of mono facial and 34 % for bi-facial silicon based solar cells. The large difference is due to the fact that bi-facial cells used 70 % of aluminium alloys of mono facial ones. While the human cancer toxicity of aluminium frames originated from the disposal of red mud from bauxite digestion in the supply chain of primary aluminium (Zhang et al., 2017), that of silicon wafers came from the electricity consumption of coal fired power (Jia et al., 2021).

Regarding ecotoxicity impacts, the manufacturing stage contributed more than 60 % of the total life cycle impact, regardless of the type of solar cells. Specifically, manufacturing stage accounted for 97 % to 100 % of the whole life cycle of PSC (Zhang et al., 2017). For silicon solar cells, PERC and module fabrication accounted for up to 70 % of the total life cycle freshwater toxicity impacts (Lunardi et al., 2019), and silicon wafers contributed to about 60 %–70 % of the total life cycle freshwater toxicity impact, mainly due to the monocrystalline silicon ingot manufacturing (Jia et al., 2021).

For abiotic depletion, the manufacturing stage is the hotspot during the life cycle of SSC. According to Lunardi et al. (2019), the highest impact originates from module fabrication, followed by PERC cells, Si wafers, EGS and mono c-Si. This is due to the consumption of materials such as glass and aluminium used in the module manufacturing phase, and metals such as copper and silver used in the cell manufacturing phase. The authors pointed out that the most significant impact of ADP arises from silver-based metallization paste (Lunardi et al., 2019), which is the same result in the study of (Jia et al., 2021).

5. Conclusion

This review studied the life cycle environmental impacts of solar cells in the context of climate change and material shortage. It is identified that energy consumption and GHG emissions are indicators which attract the most attention. Other impact indicators such as material and metal depletion, ecotoxicity and human toxicity are also considered in many recent studies, due to the important role of raw materials in renewable energy technologies in general and solar PV technologies specifically.

It is observed that the manufacturing process is the hotspot for both SSC and PSC regarding all considered environmental impact indicators of energy consumption, GHG emissions, mineral and metal consumption. Energy embodied in materials of PSC accounts for up to 90 % of energy and GHG impacts, while 50 % of these impacts originate from energy consumption during the fabricating process of the SSC itself. These results indicate the crucial role of eco-design in reducing the energy consumption and GHG emissions of the solar cells over their life

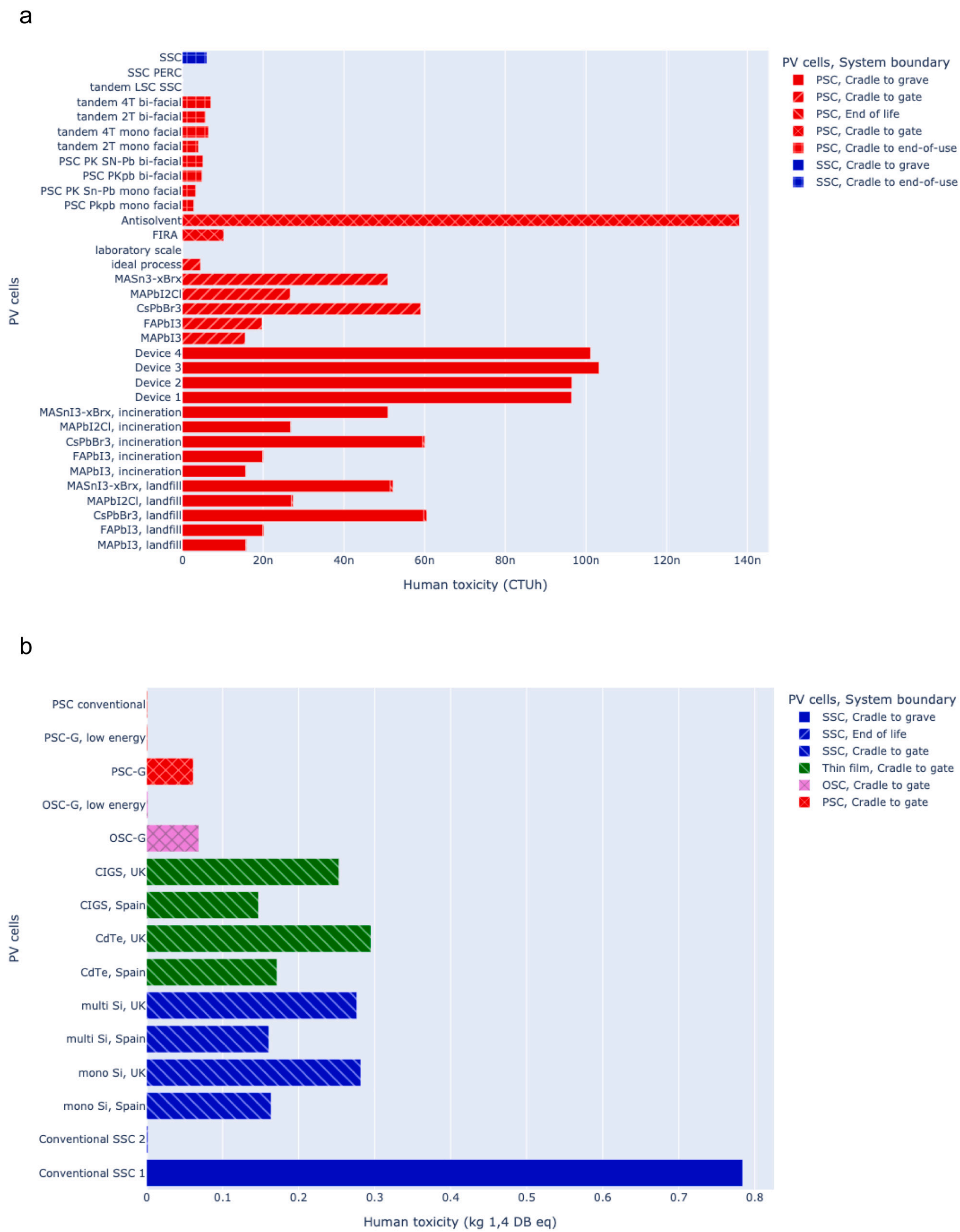


Fig. 7. a. Human toxicity of solar cells per kWh (CTUh).
b. Human toxicity of solar cells per kWh (kg 1,4 DB eq).

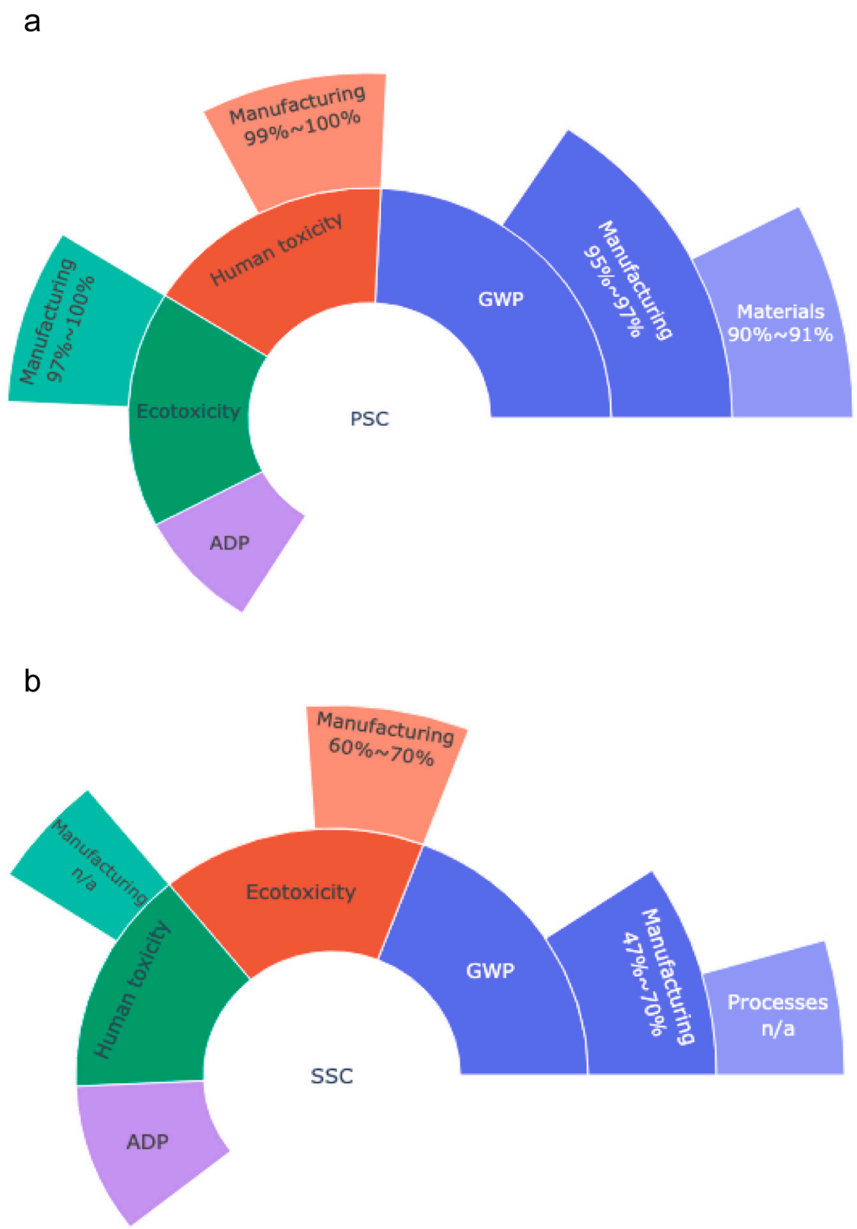


Fig. 8. a. Contribution of manufacturing stage to the life cycle environmental impacts of PSC.
b. Contribution of manufacturing stage to the life cycle environmental impacts of SSC.

cycle. The eco-design of solar cells covers different aspects such as the choice of materials, the structure or architecture of the cells, the manufacturing processes of the cells, the end of life treatment of the cells, the recovery or recycle of the materials. It helps to minimize the energy consumption during the material extraction, the cell manufacture, the waste treatment and the cell recycle, consequently, GHG emissions from those activities. At the same time, the better choice of material suggests the potential of converting into materials which are less critical and less toxic than those used in the existing technologies. All of these will support the sustainable energy and material transition.

There is a large range in the energy consumption and carbon footprints of both conventional solar cells such as SSCs, CdTe and CIGS, as well as emerging solar cells such as PSCs and tandem. This is due to the differences in methodological aspects of LCA such as system boundary, FUs and environmental indicators. Besides, the production scale of PCS and other emerging solar cells is currently at lab-scale, which makes the quantified and estimated results in some studies higher than they should be. It is expected that considering the same production scale, system boundary and FU, energy consumption and corresponding carbon footprint of emerging solar cells will be lower than those of conventional solar cells.

Regarding the material and metal consumption of solar cells, it is likely that the ADP of emerging solar cells will be lower than conventional cells. The existing literature concerned on the material and metal consumption in general, without any concentration on the links between critical raw materials and emerging solar cells. In the context of material shortage, future LCA studies should be applicable to the requirement of critical raw materials for solar PV. Besides, emerging solar cells with new materials such as perovskite and tandem cells may use some toxic materials, while the conventional SSCs use the abundant, cheap and non-toxic material of silicon. It is, consequently, recommended that the toxicity of emerging solar cells, both ecotoxicity and human toxicity should be taken into account during the design of emerging solar cells.

This review limits in the most common impact indicators of solar cells such as energy consumption, GHG emissions, material and metal depletion, ecotoxicity and human toxicity. In fact, the life cycle impacts of solar cells go beyond these above mentioned impacts. For example, solar cells are frequently installed in sunshine locations, which are dry and have limited water. Meanwhile, water is used intensively to clean the solar cells. Besides, water is an important resource for agricultural activity. With regards on the potential development and exploitation of solar agrivoltaics, the impacts on water consumption, consequently, should be taken into consideration in the future research.

Nomenclature

a-Si	amorphous silicon based solar cell
ADP	abiotic depletion
BIPV	building integrated solar photovoltaics
c-Si	crystalline silicon
CdTe	cadmium telluride
CED	cumulative energy demand
CEY	cumulative energy yield
CI(*G*)S	copper indium (gallium) selenide
CML	a life cycle impact assessment method developed by Centrum voor Milieukunde Leiden
CTU	comparative toxic unit, a unit to express the estimated increase in morbidity in the total human population (or potentially affected fraction of species) per unit mass of a chemical emitted (cases per kilogram)
DALY	disability-adjusted life year, a unit to express the loss of the equivalent of one year of full health
DSSC	dye sensitized solar cell
EGS	electronic grade silicon
EPBT	energy payback time
EROI	energy return on investment
ETP	ecotoxicity
EU	European
FFDP	fossil fuel depletion potential
FIRA	flash infrared annealing
FU	functional unit
GaAs	gallium arsenide
GHG	greenhouse gas
GTE	graphene transparent electrode
GW	gigawatt
GWP	global warming potential
HTP	human toxicity
IEA	International Energy Agency
InP	indium phosphide thin-film cell
kg	kilogram
kg 1,4 DB eq	kilogram of 1,4 dichlorobenzene equivalent
kg Cu eq	kilogram of copper equivalent
kg Fe eq	kilogram of iron equivalent
kg Sb eq	kilogram of antimony equivalent
kgCO_2eq	kilogram carbon dioxide equivalent
kWh	kilowatt hour
LCA	life cycle assessment
LSC	luminescent solar concentrator
m^2	square meter
m^3	cubic meter
MJ	megajoule
mono-Si	mono-crystalline silicon
multi-Si	multi-crystalline silicon
MWh	megawatt hour
NER	net energy ratio
OSC	organic solar cell
PAF	potentially affected fraction, a unit to express the estimate potentially affected fraction integrated over time (day or year) and volume (square meter or cubic meter), per unit mass of a chemical emitted.
PERC	passivated emitter and rear contact
PET	polyethylene terephthalate (plastics)
PRISMA	preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSC	perovskite solar cell
PV	photovoltaics
QDSSC	quantum dot sensitized solar cell
ReCiPe	a life cycle impact assessment method developed by RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability
Ribbon-Si	ribbon-crystalline silicon
SSC	silicon based solar cell
TFSC	thin-film solar cell
TiO_2	titanium dioxide
UNEP/SETAC	United Nations Environment Program, Society of Environmental Toxicology and Chemistry
USETox	a life cycle impact assessment model developed by UNEP/SETAC, focus on toxicity
Wp	watt peak
yr	year

CRediT authorship contribution statement

Conceptualization, M.C. and L.Q.L.; methodology, L.Q.L. and S.L.; resources, all authors; data curation, L.Q.L.; writing—original draft preparation, L.Q.L., F.G. and S.L.; writing—review and editing, all authors; supervision, M.C.. All authors equally contributed to the paper's development and writing. All authors have read and agreed to the published version of the manuscript.

Funding

This work has been developed in the framework of the project “Network 4 Energy Sustainable Transition – NEST”, code PE0000021, CUP B73C22001280006, Spoke 1, funded under the National Recovery and Resilience Plan (NRRP), Mission 4, by the European Union – NextGenerationEU.

Institutional Review Board statement

Not applicable.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the data in the supporting file and reference.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168019.

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