Renewable and Sustainable Energy Reviews 186 (2023) 113652

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems

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ARTICLE INFO

Keywords:
Thin-film solar cells
Life cycle assessment
Energy payback time
Global warming potential
Market share
Benchmarking

ABSTRACT

Thin film solar cells offer several benefits over conventional first-generation technologies including lighter weight, flexibility, and a wider range of optoelectronic tunability. Their environmental impact however needs to be investigated comprehensively to provide a clear comparison point with the first generation photovoltaics currently dominating the market. The main objective of this review is to evaluate current Life Cycle Assessment (LCA) studies conducted on thin film solar cells, highlighting the key parameters considered including life cycle stages, impact categories, and geographical locations. This included both commercially available thin film solar cells (a-Si, CIGS, CIS, CdTe, GaAs and GaAs tandem) as well as emerging (PSC, PSC tandem, DSSC, OPV, CZTS, QD) ones. A critical assessment of the results of 58 LCA studies was conducted and compared with traditional silicon based solar cells. Results indicate that emerging thin film solar cells hold great promise, as they tend to perform better than commercially available ones in the specified indicators, especially for CZTS and OPV. The assessment demonstrated that overall thin film solar cells had less energy requirement and better environmental performance than conventional crystalline silicon solar cell systems. However, due to their lower efficiencies their energy payback time was higher. This review provides a benchmark for the environmental LCA of different thin film solar cell technologies in order to highlight the relevance of these devices for sustainable energy generation and to give manufacturers and LCA experts information and a basis for future evaluation of solar cells.

1. Introduction

The world is experiencing a critical energy transition and is swiftly shifting away from the use of fossil fuels, toward cleaner renewable forms of energy with a target to reduce the adverse energy-related environmental emissions by 70% before 2050 compared to current levels [1]. According to the International Renewable Energy Agency (IRENA), a complete decarbonisation of energy use must be accomplished in less than 50 years in order to effectively achieve such ambitious goals and sufficiently limit the negative effects on climate change [2]. This is due to significant geopolitical decisions, particularly the Paris Agreement, calling for a worldwide reduction in carbon emissions [3]. Despite the fact that the global economy will triple by 2060, this cannot be accomplished without renewable energy sources expanding at least seven times faster than the current growth rate [2]. Aligned with this trend, the global grid-connected solar capacity increased from an annual additional power generated by solar power installation of 139.2 GW (GW) in 2020 to 167.8 GW in 2021 (equivalent to an 21% increase), setting yet another sector annual installation record [4].

According to IRENA's 2019 Future of Solar Photovoltaics report [1], rapid adoption of solar cells alone would account for 21% of overall emission mitigation potential in the energy sector among all low-carbon technology alternatives. To reach this target, solar cells are anticipated to be the second-largest source of power by 2050, paving the path for global energy sector transformation. Globally, solar cell deployment is expected to continue to break records, with annual additions reaching 162 GW by 2022, about 50% higher than the pre-pandemic level of 2019 [5,6]. However, advancement in production processes and improvement in technologies of thin-film solar cells, such as the reduction of the thickness of solar cells, the consumption of raw materials, and the increase in the rates of recycling materials, can help in further reducing

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https://doi.org/10.1016/j.rser.2023.113652
Received 4 October 2022; Received in revised form 31 July 2023; Accepted 14 August 2023
Available online 2 September 2023
1364-0321/

Abbreviations

Solar cells

a-SH	Hydrogenated amorphous silicon
a-Si	Amorphous silicon
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper indium selenide
CPV	Concentrator photovoltaics
c-Si	Crystalline silicon
CZTS	Copper zinc tin sulfide
CZTSSe	Copper zinc tin sulfoselenide
DSSC	Dye-Sensitized Solar Cell
GaAs	Gallium Arsenide
GaInP	gallium indium phosphide
Mono-Si	Monocrystalline silicon
multi-Si	Multicrystalline silicon
nc-Si	nanocrystalline silicon
OPV	Organic Photovoltaic
OSC	Organic solar cells
PCS-Sn	Tin based perovskites
PSC	Perovskite Solar Cell
QD	Quantum Dot
QDPV	Colloidal quantum dot photovoltaics
QDSSC	quantum dot sensitized solar cell
Sb_2Se_3	Antimony triselenide
SHJ	Silicon heterojunction
Si	Silicon
Zn_3P_2	zinc phosphide

Impact categories

AP	Acidification potential
CED	Cumulative energy demand
EP	Eutrophication potential
EPBT	Energy payback time
Ex	Ecotoxicity
GWP	Global Warming Potential
HT	Human toxicity
MAE	Marine Eutrophication

Nomenclature

BOS	Balance of systems
CCS	Carbon capture and storage
CSEM	Center for Electronics and Microtechnology
EC	European Commission
EOL	End of Life
EPFL	École polytechnique fédérale de Lausanne
GHG	Greenhouse gas
HZB	Helmholtz Center Berlin
ILCD	International life cycle data system
IRENA	International Renewable Energy Agency
LCA	Life cycle assessment
LCI	Life cycle inventory
PCE	Power conversion efficiency
SM	Supplementary material

the life cycle energy requirement and the environmental impacts of solar cell systems in the near future.

Solar power had a 56% share of the total new power generating capacity of renewable energy installed globally in 2021, compared to other energy production technologies (i.e. other renewable energy, hydro, wind, etc.) [7]. Despite the fact that solar cells facilitated twice as much new energy generation capacity than fossil fuels, they only generated 3.1% of the global power generation in 2020 [7], highlighting the need for higher installed capacity globally. Fig. 1 shows the top 10 countries worldwide by total installed capacity of solar cell technologies in 2020. Note that the total global installed capacity is 139.2 GW and the total installed capacity of the top 10 countries is 111.9 GW. In 2020, China remained the market leader, adding more than twice as much solar energy capacity as the second-largest market and more than the next five major markets combined. After two years of decline, the Chinese market thrived in 2020, adding 48.2 GW, a 60% increase over the 30.1 GW installed in 2019. In 2012, Europe held the highest share (58%) of the worldwide solar cells market but this changed dramatically in 2014 (dropping to 28%) as Asia overtook Europe, currently accounting for 17% of the global market in 2020 [7].

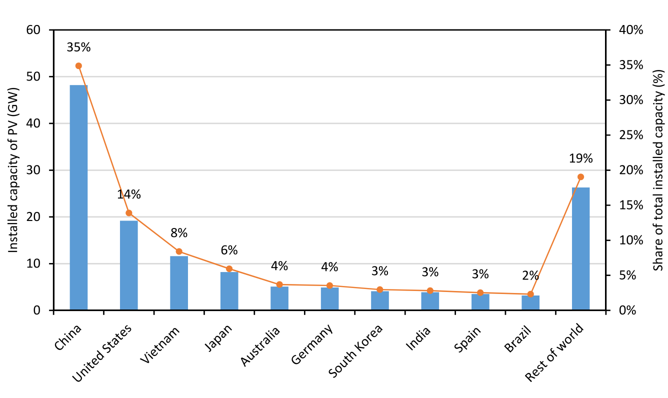


Fig. 1. Top 10 countries worldwide by total installed solar cell technologies' capacity (138.2 GW) in 2020. Data source [7].

The global installed solar cell amount is fast increasing, and this trend is projected to continue in the coming years with the lifetime of a solar cell being 25 years [8]. It is worth mentioning that the 25 years lifetime is the minimum expected lifetime for a panel, which can vastly outlast this value if properly managed (e.g., when properly encapsulated, particularly for silicon-based technologies). Manufacturers often offer a 25 year warranty (at 80% of the nominal power) for their products [8].

Moreover, by 2050, the total amount of end-of-life (EOL) solar panels is predicted to reach 9.57 million tonnes [9]. Solar cells are typically categorized into two main types based on their device structure and architecture. The first generation includes wafer-based solar cells, primarily composed of crystalline silicon (c-Si). On the other hand, the second and third generations encompass thin-film technologies. These thin-film solar cells can be further classified into silicon-based thin films, such as amorphous silicon (a-Si) and micromorph silicon (a-Si/c-Si), as well as non-silicon-based thin films, including perovskites, and chalcogenide cells such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and copper zinc tin sulfide (CZTS) cells. Unlike wafer-based solar cells, which are made from slices of semiconducting wafers generated from ingots [10], thin-film cells employ insulating substrates such as glass or flexible polymers for the deposition of layers of semiconducting materials that will make up the device structure [11, 12]. Stainless steel is also a common flexible substrate that despite its drawbacks allows for higher processing temperatures than flexible polymers.

Fig. 2 depicts the market share of solar cells by technology group. Conventional crystalline silicon (c-Si) cells have historically dominated the worldwide solar market (>90%). Poly or multicrystalline silicon (multi-Si) is leading the market ahead of monocrystalline technology

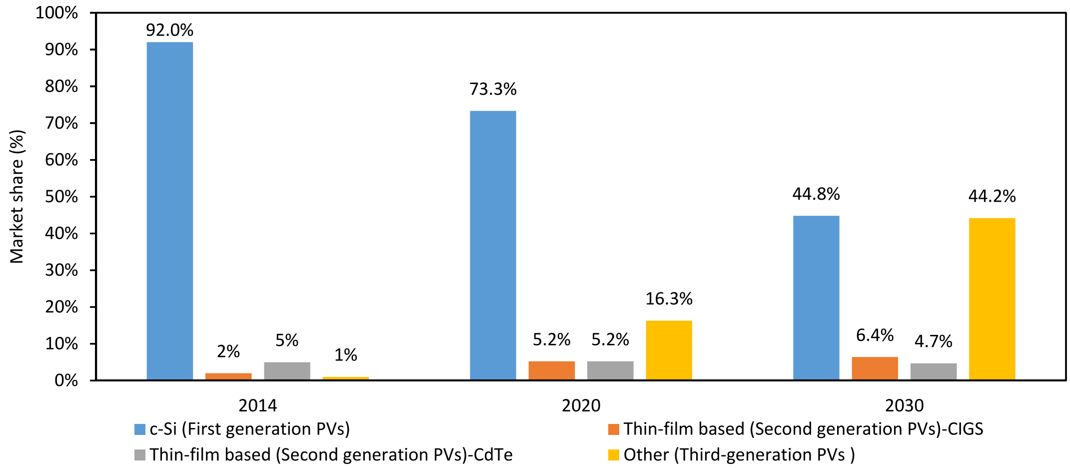


Fig. 2. Market share of solar cells by type of technology during the period: 2014–2030. It includes actual data from 2014 and numerical extrapolations for 2030. Data source: [13].

(mono-Si), accounting for 55% and 36% in 2014, respectively. In the thin-film market, CdTe cells lead with an annual production of 5%, followed by CIGS and amorphous silicon (a-Si), both around 2% each, and other technologies (dye-sensitized, CPV, organic hybrids) accounting for the remaining 1% of the market share in 2014. Between 2014 and 2030, the market share of c-Si solar cells is expected to drop from 92% to 44.8%. Over the same period, third-generation solar cells are expected to increase by 44.1%, from a base of 1% in 2014 [8,9,13]. The current deployed solar cell capacity of 138.2 GW splits up into 101 GW crystalline silicon (73.3%) and 36.9 GW thin-film (26.7%) solar cell technologies in 2020 [13].

All three generations of solar technologies have been widely researched in terms of reaching reliability, cost-effectiveness, and high efficiency. While wafer technology can attain great efficiency, thin-film can achieve the same goal with less material usage and reduced processing temperatures. Both goals must be accomplished at the same time in order to enable low-cost power generation and large market penetration of solar energy [14]. Thin-film technology for large-scale power production grew to prominence around 2006, when silicon prices increased due to rising demand, and the lack of a dedicated sector for photovoltaic-grade silicon, forcing the industry to rely on the costlier electronic-grade material. Despite its low efficiency, thin-film modules made more economic sense [1]. This explains the sudden growth of scientific articles in 2006, since then, thin-film solar cell technologies have been the focus of scientific research, as evidenced by the exponential growth in the number of papers every year (Fig. 3).

Furthermore, it is expected that next-generation multi-junction technology, stacking materials absorbing different ranges to more efficiently gather the light spectrum, address the lower efficiency issue of single junction thin-film solar cells as a result of the detailed balance limit [15]. There are numerous materials and combinations to choose from, the most promising currently appears to be a c-Si/Perovskite tandem cell structure, for which Oxford solar cell systems produced an efficiency of 29.52% at the end of 2020, predicting a practical efficiency potential of around 35% [7]. More recently, scientists at Helmholtz Center Berlin (HZB) and the Swiss Center for Electronics and Microtechnology (CSEM) and the École polytechnique fédérale de Lausanne (EPFL) achieved efficiencies of 29.8% and 31.25%, respectively [17,18].

Given the enormous interest in solar technology in particular and renewable energy systems in general, it is critical and imperative to take the necessary environmental precautions. There is a need to research the sustainability level of such renewable technologies, evaluate their environmental performance, and mitigate any potential impacts to avoid shifting the burden from an environmental impact category (or problem) to another one [19]. In this context, life cycle assessment (LCA) has proven to be an effective approach to evaluate the environmental performance of solar cell technologies [20]. This study aims to analyse the results of previous thin-film solar cell LCA studies taking into

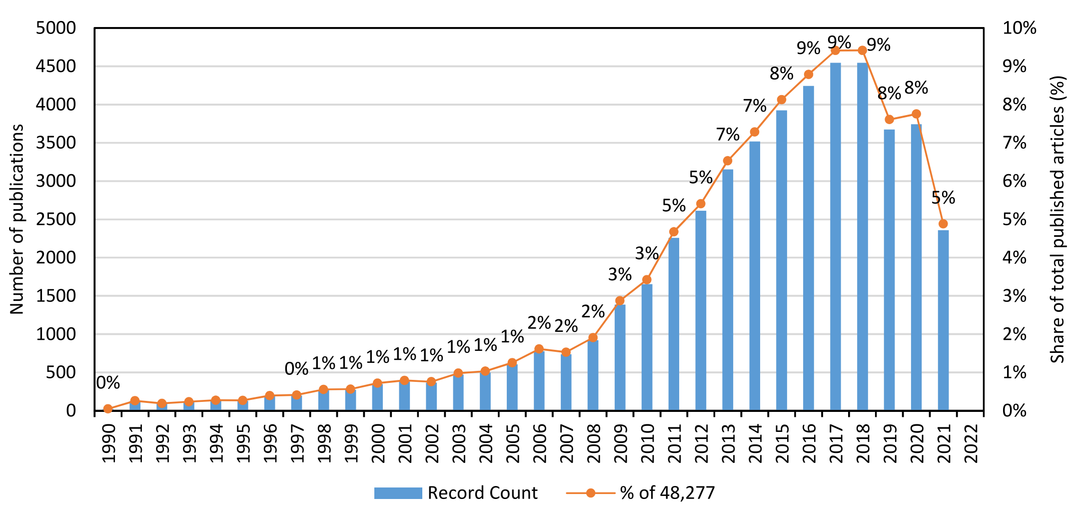


Fig. 3. Number of publications related to the search of "thin-film solar cells" from 1990 until present (focusing on research articles and review studies), retrieved from web of science on 04/10/2021 (total number of publications (articles) during this period is 48,277).

account all relevant impact categories throughout the entire life cycle of the solar cell systems, including the end-of life stage. The review scope includes LCA studies of commercial and emerging thin-film solar cell technologies compared to silicon-based solar cells. It also aims to address limitations of existing review papers on different solar cell technologies and environmental impacts presented in Section 2. A detailed description of thin-film solar cell technologies assessed in this study is demonstrated in Section 3. The benchmarking of the assessed thin-film solar cell reviewed LCA studies is presented in Section 4. The benchmarking was conducted per m^2 or for the same area of cell produced and it considered the energy requirements, energy payback time, and the environmental impacts of the assessed thin-film solar cell technologies. The ultimate objective of this study is to guide decision-making by identifying possibilities for reducing environmental impacts and improving scientific research and technological development of thin-film technologies.

2. Literature review of existing review papers

Several studies (summarised in Table 1) have contributed to the current literature related to environmental LCA applied to different types of thin-film solar cell systems by reviewing the main studies related to the topic. For instance Ref. [21], reviewed LCA studies of thin-film solar cell technologies that have a holistic coverage in their environmental assessments and highlighted that the majority of studies lack a specific description of which processes or sections of the solar cell life cycle were taken into account by the LCA studies under review. Similarly [20], provided a review of LCA studies applied to solar cell systems, and focused on the key components related to thin-film solar cell technologies and the methodological insights of these studies. However, the two studies did not provide a benchmarking of different indicators related to thin-film technologies.

Other studies have focused in their review on the detailed description of the main components of thin-film solar cell devices. For example [22], conducted a detailed review of a number of solar cell technologies in terms of historical development, materials architecture, fabrication processes, operating principles and performance parameters, scale up and stability issues as well as cost implications and alternative selective contacts of perovskite solar cells in comparison with existing solar cell technologies. This study presented an overview of the various types of cells on the market, yet it lacked progress on environmental sustainability.

Until now, scientific review papers (as demonstrated in Table 1) concerning LCA of thin-film solar cell technologies have focused on collecting data related to two indicators: (1) climate change/global warming impact category (considering greenhouse gas (GHG) emissions) and (2) energy-related indicators such as cumulative energy demand (CED) and energy payback time (EPBT). Some studies have considered both indicators while others have considered only one of those. The purpose of these reviews was primarily on comparing the environmental performance or energy outputs of solar cell technologies with other renewable technologies (e.g. such as wind energy) or for comparative purposes when a developed solar cell technology is being assessed. Studies focusing on GHG emissions only, in the context of solar cell manufacturing, have neglected other important environmental parameters and emissions such as NO_x and SO_2 [23]. Only a few review studies [21,23–26,39] go beyond that, looking at various types of environmental impacts (e.g. human health, land use, resource depletion) or investigate the contributions of individual system components to the overall environmental impact.

Other major limitations in existing review studies are related to thin-film solar cell coverage and technological scope that is limited to few technologies, as demonstrated in Table 1. For example [27], has explored the environmental implications of OPVs in terms of several indicators such as CED, EPBT, and other GHG emissions. Their effort, however, was limited to solely OPVs, excluding other technologies, and

Table 1
Past efforts at reviewing thin-film solar cell technologies.

Reference	Thin-film solar cell coverage	Review scope	LCA review[a]	Technical review[b]
[98]	a-Si, chalcogenide-based cells	Reviewed materials, technologies and commercial status of thin film cells	No	Yes
[31]	a-Si, CIGS	Reviewed and compared GHG emissions results of existing LCA studies	Yes	No
[32]	a-Si, CdTe, CIS, DSSC	Presented an overview focusing on GHG emissions and EPBT	Yes	No
[33]	a-Si, CdTe, CIGS	Reviewed 109 research, and harmonised the estimates of GHG emissions by aligning the assumptions, parameters, and system boundaries	Yes	No
[34]	a-Si, CdTe, CIGS	Compared the energy payback time and greenhouse gas emissions of commercial solar cell systems	Yes	No
[27]	OPV	Reviewed the available LCA literature on organic photovoltaics while covering several indicators such as CED, EPBT, and other GHG emissions	Yes	No
[35]	a-Si, CdTe, CIGS, GaAs, OPV, DSSC, QDPV	Examined the carbon footprint of introducing carbon capture and storage (CCS) and solar cell technologies	Yes	No
[36]	a-Si, CdTe, CIS	Provided a review of life cycle assessment of energy payback and carbon footprint of solar cells	Yes	No
[23]	a-Si, CdTe, CIGS	Reviewed GHG and other emissions, critically examining the LCA methodology framework and choices as well as their impact on outcomes	Yes	No
[37]	a-Si, CdTe, CIS	Analysed the variability of previous LCA studies in assessing GHG emissions of renewable energy technologies (for electricity and heat generation)	Yes	No
[24]	a-Si, CdTe, CIGS, OPV	Provided an overview on gaps in information related to environmental and health concerns	Yes	No
[29]	a-Si, CdTe, CIS, GaAs	Provided an overview of LCA studies highlighting exclusion of Balance	Yes	No

(continued on next page)

Table 1 (*continued*)

Reference	Thin-film solar cell coverage	Review scope	LCA review[a]	Technical review[b]
		of the System components and end-of-life stage		
[38]	a-Si, CdTe, CIGS, a-Si/nc-Si, OPV, DSSC, QDPV	Reviewed LCA studies covering GHG emissions and assessed factors that affect emission results	Yes	No
[25]	a-Si, CdTe, CIS, DSSC	Collected data on different environmental impacts (e.g. acidification, eutrophication, global warming, photochemical ozone formation, etc.) and harmonised the results for the comparison of renewable technologies	Yes	No
[26]	a-Si, CdTe, CIGS	Reviewed LCA studies of solar systems focusing on environmental impacts and cumulative energy demand	Yes	No
[39]	a-Si, CdTe, CIS	Compared the environmental impacts of perovskite cells with commercial technologies	Yes	No
[21]	a-Si, CIGS, CZTS, CdTe, OPV, GaInP, PSC, a-Si/nc-Si,	Provided a critical review of LCA studies of thin-film solar cell technologies	Yes	No
[30]	a-Si, CIGS, CdTe, CIS, DSSC	Reviewed LCA studies on GHG from different material-based photovoltaic	Yes	No
[11]	a-SH, CdTe, CIGS, CZTS, OSC, DSSCs, QDPV	Reviewed perovskites in comparison with other photovoltaic technologies	No	Yes
[14]	a-Si, CIGS, CdTe, PSC, CZTS, QD	Reviewed thin film solar cell technologies and challenges. Considered the evolution of each technology in both laboratory and commercial settings, as well as market share and reliability	No	Yes
[40]	DSSC, PSC, and QDSSC	Provided a review and analysis of LCA studies on thin-film solar cell technologies	Yes	No
[41]	a-Si, CIGS, CZTS, CdTe, DSSC	Reviewed five major thin-film solar cells, focusing on the growth technologies, layer materials and efficiencies	No	Yes
[42]	Single-junction and tandem perovskite	Provided a critical review of Life-cycle environmental impacts of perovskite solar cells	Yes	No
[43]	Chalcopyrite Cu (In,Ga)Se_2 (CIGSe), kesterite $Cu_2ZnSn(S,Se)_4$ (CZTSSe), CdTe, Sb_2Se_3 and inorganic perovskite CsPb (I1xBrx)3	Provided an overview of the progress of materials, challenges and strategies	No	Yes
[20]	a-Si, GaAs, CdTe, CIGS, CIS, Hybrid (combination of a-Si and c-Si), PSC, OPV and polymer solar cells, DSSC, QDs	Reviewed life cycle assessment of Solar photovoltaic cells	Yes	Yes
[28]	PSC, SHJ, Si, CIGS, CZTS, PCS-Sn	Reviewed perovskite solar cells in comparison with other photovoltaics technologies from the point of view of life cycle assessment	Yes	No
[44]	a-Si, GaAs, CdTe, CIGS, CIS, Hybrid ybrid (combination of a-Si and c-Si), PSC, DSSC, QDs	Review of environmental impacts of commercial and emerging solar energy technologies	Yes	No

[a] LCA review: Coverage of impact categories and life cycle stages of thin-film solar cell technologies.
[b] Technical review: Provides a technical coverage/review of materials, mainly on the cell structure/material configuration, deposition method, technologies considered, efficiencies, and/or commercial status.

made no advancement toward environmental sustainability [27]. The work of [28] have reviewed the life cycle sustainability of perovskite solar cells in comparison to commercially available solar cell technologies. However, this work did not consider other types of emerging thin-film solar cell technologies. Similarly [29], did not consider the emerging solar cells. Their work have mainly assessed the EPBT and CO_2 emissions of some solar cell technologies, neglecting other environmental indicators. In addition, it lacked the assessment of the technical properties of the solar cells and the component of the balance of systems (BOS). Furthermore, the work of [30] was limited to GHG emissions and did not consider emerging solar cell technologies.

It is worth noting that given the very fast-paced nature of the developments in this field, older papers on the list need to be reviewed with that consideration in mind.

As demonstrated in Table 1, previous review papers lack a systematic evaluation of the environmental issues coupled with a comprehensive technical coverage of thin-film solar cell technologies, making them difficult to be used for holistic benchmarking studies. In order to address this gap, our study aims to provide an in-depth technical coverage of thin-film solar cell technologies in Section 3, highlighting the advantages and disadvantages of different types. Additionally, Section 4 presents a thorough review of Life Cycle Assessment (LCA) studies, specifically focusing on three key indicators: energy requirement, EPBT, and GWP, while also considering other environmental impact categories associated with thin-film solar cell modules. In this work, the significance of using LCA is studied, with the goal of: 1) identifying the environmental hotspots to reduce the environmental impact of materials and processes; 2) developing credible benchmarking procedures; 3) improving design policies for sustainable consumption and production; and 4) establishing a baseline of information on an entire system for certain processes within current or predicted practices.

3. Description of thin-film solar cell technologies

Thin-film solar cells are divided into two categories: commercial (second generation solar cells, presented in Table 2) and emerging or innovative thin-film technologies (third generation solar cells, presented in Table 3) [45]. Among the most popular commercial thin-film solar cells are: 1) amorphous and nanocrystalline silicon (a-Si and nc-Si); 2) copper indium gallium diselenide (Cu(In, Ga) Se_2 or CIGS)/copper indium selenide (CIS); 3) cadmium telluride (CdTe) and cadmium sulfide (CdS); 4) gallium arsenide (GaAs); and 5) tandem/multi-junctions modules based on Si [20,21].

It is worth noting here that the classification of GaAs in the literature is debatable. While some studies [20,21] categorize it under thin-film solar cells, other studies [22,44] classify it under wafer-based solar cell technologies. However, GaAs layers are indeed thin and the bandgap direct, the fabrication processes, applications, performance, and

Table 2
Efficiencies, advantages and disadvantages of commercial (second generation) solar cells in comparison to the first generation-conventional crystalline silicon (c-Si).

Thin-film solar cell type	Description	Performance	Advantage	Disadvantage	Source
a-Si	First developed in 1965 using silfrom silane gas (SiH_4). Hydrogenation is deployed during fabrication to reduce the density of dangling bonds and increase photoconductivity. Usually configured in the n-i-p or p-i-n sequence by plasma enhanced chemical vapour deposition method. Other deposition methods such as cyclotron resonance, hot-wire, photo chemical vapour deposition methods and sputtering can also be been applied.	● 9.5–12.24% efficiency reported by manufacturer (8% commercial efficiency) ● 14% laboratory scale/ best research-cell efficiency ● Bandgap (1.7 eV)	● Low-cost production compared to c-Si and cheapest on the market	● Low solar conversion efficiency and stability compared to c-Si, due to thinner layers thus less materials for solar absorption	[20,22, 41,44, 46–48]
CIGS/ CIS	Discovered in 1953 by Hahn. The cell is fabricated from alloying varying quantities of $CuInSe_2$ with $CuGaSe_2$. Glass substrates are most commonly used to develop the cell, however flexible substrates such as polymers and metal foils have recently been used. Deposition methods used for its absorber are mainly physical vapour deposition methods such as thermal co-evaporation. CIS was invented by Hahn in 1953. Similar in structure to CIGS but has a lower efficiency due to the absence of gallium. Deposition methods are similar to the physical vapour deposition methods used in CIGS.	● 9.5–12.24% efficiency reported by manufacturer ● 20–23.4% laboratory scale/best research-cell efficiency ● Bandgap (1.0–1.68 eV) CIS: 10–13% efficiency	● As efficient as c-Si solar cells ● Less energy consumption for manufacturing compared to c-Si ● Good heat resistance compared to c-Si	● Use of toxic chemicals ● Very expensive due to the use of scarce elements and materials such as gallium and indium ● Difficulty in controlling film stoichiometry and properties	[20,41, 48–57]
CdTe	CdTe single junction cell having an efficiency of 2% was first reported in 1956 by Rappaparot. Made up of cadmium telluride crystals, which can be arranged in either substrate or superstrate design. Its absorber layer can be deposited using numerous techniques including screen-print deposition, spray deposition, sputter deposition, physical vapour deposition, metal organic chemical vapour deposition, close space sublimation, electrodeposition and sintering. Close space sublimation deposition method tend to produce the best performing CdTe cells.	● 8.51–18.6% efficiency reported by manufacturer ● >22% laboratory scale/ best research-cell efficiency ● Bandgap (1.45 eV)	● Leading thin-film solar cell technology market ● Have a high range of wavelength spectrum that can be absorbed compared to c-Si ● Offer the lowest costs of module as compared to other commercialised solar cell technologies as Cadmium is abundant ● Very well suited for large area fabrication	● Causes toxicity due to the use of Cadmium ● Scarcity and material criticality (use of tellurium)	[20,22, 41,48, 58,59]
GaAs	Deployed initially by Russia in the 1960s for the Venera 3 mission. It is made up of gallium arsenide which has numerous technical advantages such as high optical absorption coefficients and ideal direct bandgap. The liquid encapsulated Czochralski technique and Bridgman process are both used to grow single GaAs crystals for deployment in solar cells.	24.1–29% efficiency	● High efficiency and less thickness compared to c-Si	● High production cost due to factors such as imperfections of its crystal, limiting its large-scale deployment (£3000 compared to £3 for c-Si)	[20,22, 48,60, 61]
c-Si	Most commonly available commercial thin film solar cells having been produced for over 50 years. First manufactured in 1954 by Bell laboratory. Single or multicrystalline silicon slices are used to manufacture the cells. The Czochralski process, float-zone or Bridgman process can be used to develop single crystal silicon cells while silcon feedstock through casting technology are used to produce multi crystal silicon cells.	● 14.9–21.5% efficiency ● Bandgap (1.1–1.2 eV)	● Most commonly used solar cell technology ● Long-term track record based on performance, durability, and reliability ● Has a stable photo-conversion efficiency ● Has non-toxic elements ● Strong industrial experience and knowledge background inherited from the semiconductor industry	● Poor light absorption due to its indirect energy bandgap ● High level requirements for material purification ● Reliance on silicon and silver for production	[22,48, 62–65]

a-Si: amorphous silicon, CIGS: copper indium gallium selenide, CdTe: cadmium telluride, GaAs: gallium arsenide, c-Si: crystalline silicon; CIS: copper indium selenide.

Table 3
Efficiencies, advantages and disadvantages of emerging (third generation) solar cells.

Thin-film solar cell type	Description	Performance	Advantage	Disadvantage	Source
CZTS	Katagiri and co researchers reported the first CZTS cell in 1997 with an efficiency of 0.66%. Cu_2ZnSnS_4 (CZTS) cells are made up of kesterite crystal structures, which are non-toxic earth abundant materials. Numerous deposition methods including vacuum, vacuum free and solution-based methods are usually used to deposit its absorber layer.	● 10–13% efficiency ● Bandgap (1.5 eV)	● Does not contain rare metals or toxic materials and can be combined with cadmium-free buffer layer ● Tunable optoelectronic properties, and material stacking often transferable from CIGS	● Lower conversion efficiency in comparison to silicon based solar cells due to the presence of a high concentration of native material defects	[22,41,48]
PSC	Invented in 2009 with exponential growth in cell efficiency (3%–22%) till date. Manufactured using perovskites which are compounds having similar structures to calcium titanate CaTiO3. Cells can be assembled in either the mesoscopic or planar device architecture. Perovskite absorber layer can be deposited using spincoating, thermal evaporation, inkjet printing, drop casting, doctor blade coating, slot die coating, and spray coating. The most common method of depositing method is spincoating and thermal evaporation.	● 19–22% laboratory scale/best research-cell efficiency	● Cheaper production compared to c-Si because it is made from inexpensive and plentiful elements ● Good efficiency and potential for improvement and development ● Good and tunable direct bandgap, a substantial absorption coefficient, and long electron and hole diffusion lengths	● Quick break down with exposure to heat, snow, moisture, etc. ● Toxicity issues, particularly in relation related to the use of lead and solvents	[20,22,44,48,66–68]
OPV	Pochettino first recorded the photoconductivity of the organic compound anthracene in 1906. This set the scene for the future developments of OPV. OPV usually comes in the bulk heterojunction architecture, where a polymer or small molecule is the electron donor and fullerene or non-fullerene molecules are used as the electron acceptor. The organic materials can be deposited using spin coating and screen printing alongside low cost methods such as inkjet printing and spray deposition method.	● 4–9% efficiency ● 18.2% laboratory scale/best research-cell efficiency	● Lightweight, mechanical flexibility, disposability, and roll-to-roll production capacity on a wide scale	● Inadequate efficiency, durability, and stability	[20,48,69–73]
DSSC	The photoelectric effect of organic dye was first detected at the end of the eighteenth century. However, DSSC as we know it today was created in 1988 by Brian O'Regan and Michael Grätzel. Originally, ruthenium dye was deployed in DSSC, although numerous organic and inorganic dyes have also been reported for this purpose. Spin coating deposition method is widely used for preparation of the transparent conducting oxide layer on the electrodes with theTiO_2 layer for absorption of the dye deposited using spin coating, spray coating, screen printing and electrophoretic deposition methods.	● 10–12.3% efficiency ● 13% laboratory scale/best research-cell efficiency	● Relatively low manufacturing costs due to the use of small quantities of low-cost and readily-available materials and simple process ● Can be recycled due to less pollutant ● Simple assembly and flexible modules ● Compatibility with printing techniques and integration with a variety of surfaces ● Deposition on a variety of substrates ● Work in low-light conditions	● Reduced power production and potential physical damage due to freezing of electrolyte at low temperature ● Must be tightly sealed because it includes volatile organic solvents ● Issues with long-term stability under high temperature ● Low absorption coefficients	[20,22,41,48]
QD	QD solar cells incorporates solar energy harvesting colloidal quantum dots, which are nanocrystals developed from semiconductor materials. These materials initially included toxic chemicals such as CdSe, CdTe and CdS but has expanded to include more non-toxic materials such as InAs, InP and $CuInS_2$ that cover both the visible and infrared spectral range. QDSC come in either the schottky, depleted heterojuction, quantum junction, band alignment or tandem device structures. Solution based deposition methods such as Spincoating, dip coating, drop casting, inkjet printing, spraycoating, doctor blade coating and slot die coating can be deployed to coat the cells.	● 1.9–9.2% efficiency ● 18.1% laboratory scale/best research-cell efficiency	● Potential of easy fabrication and air-stable operations	● Low efficiency due to poor light absorption properties ● Low understanding of surface chemistry ● Inadequate open-circuit voltages and mobility of the charger carrier	[11,20,48,74]
Tandem PSC	Involves coupling PSC with other solar cells in order to increase its efficiency beyond the Shockley-Queisser limit. The top and bottom solar cells can be connected either	● 6–27% efficiency ● Perovskite/CIGS tandem: 24.2% laboratory scale/best	● Most promising solar cell technology ● Low environmental impacts		[22,28,42,48]

(continued on next page)

Table 3 (*continued*)

Thin-film solar cell type	Description	Performance	Advantage	Disadvantage	Source
	as 4-terminal, 2-terminal or optical splitting tandem cells. PSC have been coupled with DSSC, C-Silicon, CIGS as well as other PSCs. Deposition methods remain the same for each of the absorber layers of the coupled cells in the tandem configuration.	research-cell efficiency ● Perovskite/Si tandem: 31.3% best research-cell efficiency ● Bandgap (1.7–1.8 eV)			

CZTS: kesterites or copper zinc tin sulphide, PSC: perovskite solar cells, OPV: organic photovoltaics, DSSCs: dye-sensitized solar cells, QD: colloidal quantum dot, c-Si: crystalline silicon

timeframe during which this technology was developed is more akin to a first generation type of solar cells.

The direct optical bandgap of commercial thin-film solar cell materials enables efficient light absorption in the range of 10–100 times higher compared to conventional silicon-based solar cells. This increased light absorption capability allows for the utilization of films that can be as thin as just a few microns [20,21]. The main advantage of these technologies is the low cost due to the use of less raw materials and less complex manufacturing techniques (e.g. spray or other chemical based methods). Modern factories, for example, can manufacture thin-film modules in a highly streamlined and automated manner, resulting in modules with low per-watt costs. These technologies are produced by depositing one or more thin films of photovoltaic material onto a substrate, such as glass, plastic or metal. Thin films can be made by sputtering and reactive annealing, closed space sublimation (for CdTe), co-evaporation, spray, etc. The wide variety of possible fabrication processes is a big asset of this field and to some extent could be a limitation due to the application of different processes. In addition, due to the low thickness, commercial thin-film solar cells are easier to handle and more flexible than their silicon counterparts, and are less vulnerable to breakage [20,22]. While lower performances are often seen as a limitation of thin film solar cells, the two dominant commercial thin film technologies CdTe and CIGSe have demonstrated conversion efficiencies in the 15–20% range at panel level (with in-lab record efficiencies at 23%), on par with the performance of polycrystalline silicon but still below the more mature c-Si cells.

The main emerging (third generation) thin-film solar cells are as following: 1) kesterites or copper zinc tin sulphide (Cu2ZnSnS4 or CZTS); 2) perovskite solar cells (PSC); 3) organic photovoltaics (OPV); 4) zinc phosphide (Zn3P2); 5) dye-sensitized solar cells (DSSCs); 6) colloidal quantum dot (QD) solar cells; 7)tandem/multi-junctions modules based on PSC; and 8) upstream solar conversion concepts such as Hot Carrier, Intermediate Band, Multiexciton generation, currently without definitive proof of concept devices [20,21]. The emergence of these technologies is well aligned with the high level of research and development activities in material discovery and device engineering in recent years. They consists of nanostructured layers using semiconducting organic, inorganic, or hybrid materials to obtain certain electrical and optical features. These technologies are still in the early stages of development and commercialization and have yet to be produced at a larger scale [20,22]. Table 3 shows the efficiency of the main emerging thin-film solar cells as well as their advantages and disadvantages.

4. Review of life cycle assessment of thin-film solar cell technologies

Comparisons of different solar cell systems based on a single parameter such as efficiency is misleading since this ignores all the effects of the production and use processes. In this context, the LCA methodology was used to analyse the environmental burdens associated with thin-film solar cell technologies, by identifying energy and materials utilization and waste generation released to the environment. In this study, the collected studies were evaluated based on the degree of their coverage of the solar cell life cycle stages and the variety of environmental impact categories considered. The review presented below particularly focused on three indicators: energy requirement, EPBT, and GWP (as well as considering other environmental impact categories) of thin-film solar cell modules.

Solar cells-specific LCA aspects, such as functional unit, life expectancy, effect categories, and so on, have been compiled by the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 12 as well as Life Cycle Inventory (LCI) for key commercial photovoltaic technologies [75]. The functional unit, in this context, enables for consistent comparisons of various photovoltaic systems and other electricity-generating systems that can perform the same function [76,77]. The suggested functional unit is kWh of electricity generated, with the drawback that the calculation must be conducted assuming a lifetime for the solar cell [77,78]. However, the impact in this study was presented per unit area (m^2) to provide direct comparison of manufacturing of the cells as it is more useful to manufacturers [20,79,80]. Several other parameters are required to convert the impact findings from cell manufacture to impact results from unit electricity generated (i.e. the functional unit of the study), as shown in Eq. (1) adapted from Ref. [39].

$$Impact_{m^2} = Impact_{kWh}\ x\ I\ x\ \eta\ x\ PR\ x\ LT \tag{1}$$

where,

$Impact_{m2}$ = Impact per 1 m^2 module area;
$Impact_{kwh}$ = Impact per 1 kWh of electricity generated;
I = insolation constant (kWh/m^2 yr);
η = module efficiency (%);
PR = performance ratio of the module (%);
LT = lifetime of the PV technology (yr).

Insolation can vary based on the location and orientation of the solar cell. Similarly, the performance ratio of a solar cell can exceed 75% when it is well ventilated and properly maintained, but it can be lower than 75% due to factors such as shading and soiling if maintenance is neglected. However, in order to establish a common basis for comparison among different technologies, these parameters were harmonised, following the approach adopted by previous studies [81]. Performance ratio and insolation, for example, are frequently held constant at 75% and 1700 kW/m^2/yr, respectively, while module lifetime is frequently calculated at 30 years [81]. When it comes to efficiency, there is some ambiguity and differing viewpoints on what value should be employed. The module efficiencies were retrieved from reviewed LCA studies, when data is not available, the highest efficiency from the range of values found in Tables 2 and 3 were adopted. These were also used to calculate the Energy payback time (EPBT).

The system boundaries of the complete solar cell life cycle (cradle to grave) are depicted in Fig. 4, and is utilised as a reference in this review. It includes the production stage, which comprises all upstream processes such as resource extractions, the use stage (including installation and operation with balance of systems (BOS) such as inverters, wiring, and support structures), and the end-of-life (EOL) stage (including decommissioning and waste management of all materials, including potential recycling, treatment or disposal).

It should be noted that the evaluations of these studies in the following subsections are coupled with significant uncertainties and limitations due to lack of a comprehensive coverage of the system's life cycle or pertinent environmental impact categories. Due to the limitation in certain cases to find a representative sample of LCA studies per technology for a consistent analysis across the paper, results are distinguished among the various thin-film solar cell technologies based on commercial and emerging technologies in the following sections. Table 4 presents a summary of all main results per thin-film technology, including key-parameters (solar system type, power conversion efficiency, geographical location), and methodological aspects (life cycle stages and impacts categories). Tables S1–S9 in Supplementary Material (SM) demonstrate the reviewed LCA studies for the twelve assessed thin-film technologies. This review provides a full coverage of the different impact categories that have been reported in the literature to analyse thin-film solar cells as detailed in the SM and summarised in Table 4. Given that the cumulative energy demand (CED) and GWP are two of the most frequent impact categories used to compare photovoltaic systems [20,21]. The ranges of results of GWP and CED were derived by the authors from reviewed LCA studies for benchmarking the commercial and emerging thin-film technologies in comparison to Silicon based ones (mono-Si and multi-Si). CED measures the primary energy inputs to the specified life cycle phases in mega joules (MJ), whereas the GWP measures greenhouse gas emissions in kilogrammes of carbon dioxide equivalents (kg CO_2 eq).

Commercial thin-film solar cell technologies such as a-Si (9 scenarios) and CdTe (12 scenarios) were largely represented while CIGS (four scenarios), CIS (five scenarios), and GaAs (one scenarios) were less studied. PSC (32 scenarios), DSSC (41 scenarios) and OPV (32 scenarios) for the emerging thin film technology had generous amounts of studies and scenarios. However, for CZTS (three scenarios) and QD (one scenario) a limited number of LCA studies were identified. Overall, the number of research has risen dramatically, with two-thirds of them published between 2011 and 2018.

As Table 4 shows, 34 out of the selected LCA scenarios were related to commercial solar cell technologies with Europe, China, Japan, and United States of America (USA) represented. Among them, eight scenarios covered the whole life-cycle stages including the end-of-life stage while 19 had a cradle to gate system boundary. It is worth noting that seven scenarios did not consider the life cycle stage coverage or did not transparently report it. Moreover, only 12 scenarios considered more than two impact categories (including the GWP and CED categories) whereby the majority of scenarios (22) considered only the GWP and CED impact categories. Limiting the scope of environmental impact assessment to GWP or energy-related indicators impacts is misleading [21]. A number of studies [82–85] have conducted the normalisation of impact results, assuming the impact categories are given equal weight; resource depletion and toxic impacts tend to dominate the GWP and other impact results [21]. Therefore, LCA practitioners should consider all environmental impact categories to determine the most problematic one and avoid shifting the burdens from one impact to another. A significant number (117 scenarios) of LCA studies scenarios were found to consider emerging thin film solar cell technologies. They covered installed solar cell systems across Europe (91 scenarios), USA (19 scenarios) as well as Africa (five scenarios) Iran (one scenario) and China (one scenario). Out of these LCA scenarios, 25 scenarios had a full coverage of life cycle stages while 92 considered only the production stage. Less than 25% of the selected studies reported any form of uncertainty analysis related to the quality of their inventory data. The most common method adopted for these analyses was the Monte Carlo sampling method. Other sources of uncertainty in the LCA studies were due to the choice of parameters when selecting the scope of the study. This usually takes place in the form of choices in functional unit, timeframe and other selections related to methodology development. Sensitivity analysis adopting different scenarios helped reduce the uncertainties of these choices. The following sub-sections present a further analysis of the reviewed thin-film solar cell technologies in relation to the three assessed indicators: energy requirement, energy payback time and GWP.

4.1. Energy requirement of thin-film solar cells

Fig. 5 shows the results of energy requirements retrieved from reviewed LCA studies, which are summarised and compared to silicon-based solar cells. This is intended to assess the performance of manufacturing thin film technologies compared with the first generation solar cell technologies. For commercial thin film solar cell technologies (a-Si, CIGS, CIS, CdTe, GaAs and tandem GaAs), the life cycle CED ranged from 684 to 8671 MJ/m^2 (median: 1248 MJ/m^2). This range was higher than emerging thin-film solar cell technologies (PSC, PSC tandem, DSSCs, OPV, CZTS, QD) that reported a CED range of 37–24007 MJ/m^2 (median: 721 MJ/m^2). From median values of the assessed thin film technologies, it can be seen that OPV (103.23 MJ/m^2) has the lowest CED with GaAs (7674 MJ/m^2) and GaAs tandem (7938.5 MJ/m^2) requiring the largest amount of energy to manufacture 1 m^2 of the cells. However, as these values were from one scenario for GaAs and three scenarios for GaAs tandem, more comprehensive LCA studies need to be carried out to confirm these high values. Following GaAs and its tandem, PSC tandem has the highest CED value (3546 MJ/m^2) among the assessed solar cell technologies. The evaluation was based on lab fabrication methods. It is important to further evaluate this finding as the fabrication method for perovskite is very similar to OPV (lowest CED).

Among the twelve types of thin film solar cell technologies, only GaAs required more energy than mono-Si (4056.5 MJ/m2) and multi-Si (3924.5 MJ/m2). This indicates that the overall energy requirement of thin-film solar cell technologies is much lower than conventional crystalline silicon solar cell systems. It is important to highlight that there was no dedicated silicon purification process for producing silicon-based solar cell systems. It was also discovered that different energy allocation cases for silicon wafer production resulted in a large difference in energy requirements. We could not find a sufficient number of studies that

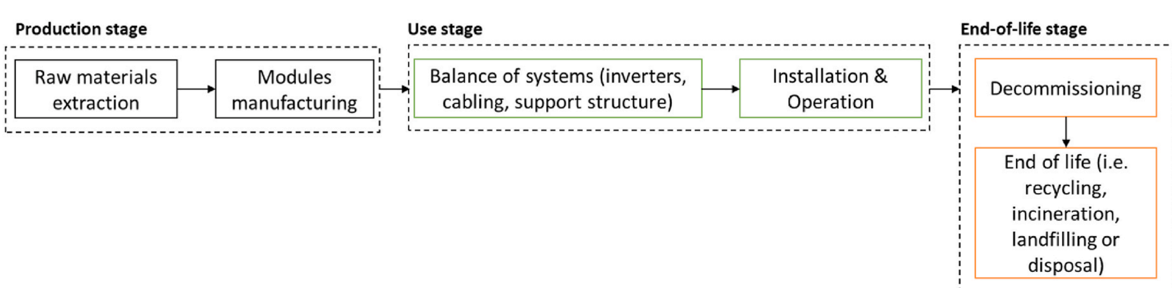
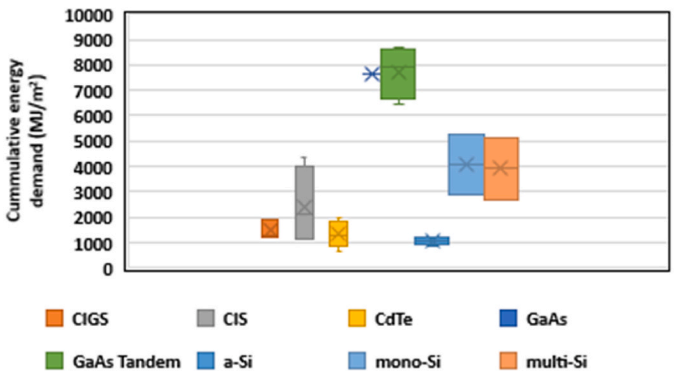


Fig. 4. Complete life cycle of solar cells' system boundaries as considered in the review.

Table 4
Summary of the main results of the reviewed LCA studies of thin-film solar cell technologies.

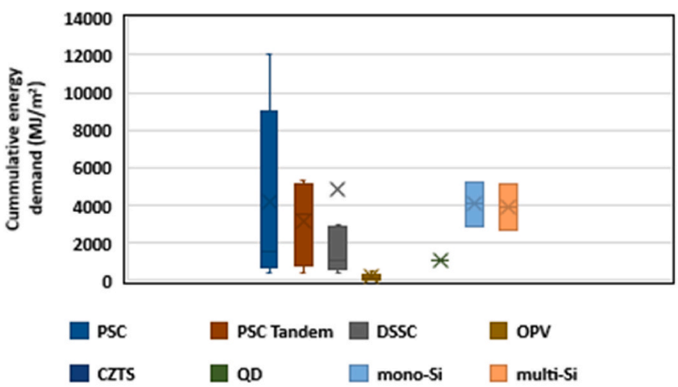
Nb of reviewed studies	Nb of reviewed scenarios	Technology	Life Cycle Stages	Impact Categories	Location	EPBT	PCE (%)	GWP ($KgCO_{2eq}/m^2$)	CED (MJ/m^2)
Commercial thin-film solar cell technologies									
7	9	a-Si	Cradle to gate (4 scenarios); Cradle to grave (1 scenario); Unspecified (4 scenarios)	GWP (7 scenarios); CED (6 scenarios); other impact categories (1 scenario)	China (3 scenarios); Europe (2 scenarios); USA (2 scenarios); Unspecified (2 scenarios)	1.03–5.5	6.3–13.6	43.05–133.88	862–1202
3	4	CIGS	Cradle to gate (3 scenarios); Unspecified (1 scenario)	GWP (4 scenarios); CED (3 scenarios)	China (1 scenario); Europe (2 scenarios); Unspecified (1 scenario)	1.01–1.45	10.5–15	34.5–91.92	1236–1936
4	5	CIS	Cradle to gate (2 scenarios); Cradle to grave (3 scenarios)	GWP (5 scenarios); CED (2 scenarios); other impact categories (2 scenarios)	China (2 scenarios); Europe (3 scenarios)	1.6–2.9	10.7–11	52.42–266.5	1117–4334
10	12	CdTe	Cradle to gate (6 scenarios); Cradle to grave (4 scenarios); Unspecified (2 scenarios)	GWP (12 scenarios); CED (8 scenarios); other impact categories (5 scenarios)	China (2 scenarios); Japan (1 scenarios); Europe (7 scenarios); USA (2 scenarios)	0.5–2.1	9–22	33.41–428	684–1971
1	1	GaAs	Cradle to gate (1 scenario)	GWP (1 scenario); CED (1 scenario); other impact categories (1 scenario)	Europe (1 scenario)	5	23.3	–	7674
3	3	GaAs Tandem	Cradle to gate (3 scenarios)	GWP (3 scenarios); CED (3 scenarios); other impact categories (3 scenarios)	Europe (3 scenarios)	1.37–4.6	28–28.5	419–454	6437–8671
Emerging thin-film solar cell technologies									
12	32	PSC	Cradle to gate (22 scenarios); Cradle to grave (10 scenarios)	GWP (32 scenarios); CED (27 scenarios); Other impact categories (32 scenarios)	Europe (22 scenarios); USA (10 scenarios)	–	6.4–21.1	10–1650	400–12060
4	8	PSC Tandem	Cradle to gate (5 scenarios); Cradle to grave (3 scenarios)	GWP (8 scenarios); CED (6 scenarios); Other impact categories (8 scenarios)	Europe (3 scenarios); USA (5 scenarios)	–	6–27	33–2066	419–5311
7	41	DSSC	Cradle to gate (38 scenarios); Cradle to grave (3 scenarios)	GWP (41 scenarios); CED (30 scenarios); other impact categories (38 scenarios)	Iran (1 scenario); Europe (36 scenarios); Africa (5 scenarios)	0.6–4.6	0.105–12	16.33–1791.62	391–24007
14	32	OPV	Cradle to gate (23 scenarios); Cradle to grave (9 scenarios)	GWP (25 scenarios); CED (13 scenarios); other impact categories (18 scenarios)	China (1 scenario); Europe (27 scenarios); USA (3 Scenarios); Unspecified (1 scenario)	0.03–5	1–15	1.36–112.03	37–490
2	3	CZTS	Cradle to gate (3 scenarios)	GWP (1 scenario); CED (1 scenario); other impact categories (3 scenarios)	Europe (2 scenarios); USA (1 scenario)	–	10–15	0.57–145.35	–
1	1	QD	Cradle to gate (1 scenario)	GWP (1 scenario); CED (1 scenario); other impact categories (1 scenario)	Europe (1 scenario)	0.9	14	25	1030

Notes: Data was compiled by authors based on reviewed LCA studies (58 (151 scenarios)) for the different thin-film solar cell technologies presented in detail in Tables S1–S9 in the Supplementary Material. Some studies considered different thin-film technologies and some others considered different scenarios within the same technology (for the purpose of covering different material configuration or parameters/assumptions). Therefore, the total reviewed LCA studies (58) reflect a total number of 151 scenarios considered per technology.
a-Si: amorphous silicon, CIGS: copper indium gallium selenide, CdTe: cadmium telluride, GaAs: gallium arsenide, c-Si: crystalline silicon; CIS: copper indium selenide, CZTS: kesterites or copper zinc tin sulphide, PSC: perovskite solar cells, OPV: organic photovoltaics, DSSCs: dye-sensitized solar cells, QD: colloidal quantum dot, c-Si: crystalline silicon



	CIGS	CIS	CdTe
Median (Mj/m^2)	1,248	2,141	1,291
	GaAs	GaAs Tandem	a-Si
Median (Mj/m^2)	7,674	7,939	1,054
	Mono-Si	Multi-Si	
Median (Mj/m^2)	4,057	3,925	

(a) Commercial thin-film solar cell technologies



	PSC	PSC Tandem	DSSC
Median (Mj/m^2)	1,578	3,546	1,108
	OPV	CZTS	QD
Median (Mj/m^2)	103	--	1,030

(b) Emerging thin-film solar cell technologies

Fig. 5. Review of cumulative energy demand (CED) during the life cycle for various thin-film solar cell technologies in comparison to conventional Si-Based technologies.

conducted hotspot analyses for each impact category to conduct a consistent analysis. The conducted hotspot analyses based on primary energy demand to determine where the greatest energy demand occurred in the manufacturing of thin-film modules. It was observed that primary energy demand is mostly influenced by electricity-intensive processes rather than materials with high embedded energy. These are mostly metal deposition methods with vacuum conditions and high temperatures, such as layer deposition across technologies. Only a few research identified embedded energy materials as hotspots with the greatest impact to energy consumption [21]. Overall, it can be deduced that the large range of reported CED values is mainly related to the deposition methods among the different assessed solar cells. For instance, a-Si uses plasma deposition, which is relatively low in terms of energy consumption. Similarly, CdTe (closed space sublimation) and CIGS (sputtering + reactive annealing) are not very energy intensive. GaAs on the other hand, being based on epitaxial methods and using wafer substrates has a much higher energy consumption.

The energy consumption of thin-film solar cell technologies can be divided into two categories: direct energy consumed during processing and embedded energy in materials. With the advancement of manufacturing technologies, there are still opportunities to lower direct process energy in the future, but it will be difficult to reduce material embodied energy further until cheaper and readily available substrate and encapsulation materials can be produced. A review by Ref. [36] showed that the frame contributes to around 15–25% energy to the total energy demand of thin-film solar cells, the frameless design is very significant for minimising the total energy requirement of thin-film solar cell modules.

[86] evaluated the energy demands of six types of solar cell modules, namely mono-Si, multi-Si, a-Si/mono-Si, thin-film Si, CIS, and CdTe, ranging from 1235 to 1747 MJ/m^2. Among the six types of solar cell modules evaluated, the CIS module had the lowest energy need of 1235 MJ/m^2 and the mono-Si module had the highest. The discrepancy in data spread between CIS and CIGS could be related to the fact that the former material was more studied in the past, while the latter has gained more popularity through the recent decade. It is worth noting that there is little fundamental difference between both compounds, which can be produced with similar processes and experimental conditions. The Ga-compound is more efficient, and is thus preferred in most cases.

Therefore, considering the CED, the a-Si solar cell modules (1054 MJ/m^2) had the best performance among commercial thin-film solar cell technologies and OPV (103 MJ/m^2) among emerging thin-film technologies.

4.2. EPBT of thin-film solar cells

The EPBT of the 12 studied thin-film solar cells compared to crystalline silicon solar cells are displayed in Table 5. It is worth noting that EPBT results in the table are normalised to the same performance ratio (0.75) and solar radiation (1700 kW h/m^2/yr) as employed by previous studies [36,39]. The ranges of power conversion efficiency were selected from those found in Table 2 for each technology with CED adopted from the reviewed LCA studies.

The EPBT was in the range of 0.8–9.44 years for commercial thin-film solar cells and between 0.09 and 52.30 for emerging thin-film solar cells. The types of modules (frame or frameless), varying efficiencies, different manufacturing materials, and energy requirements are responsible for the significant variances. The results showed that OPV (0.09–2.67) has the shortest relative EPBT due to its lower energy consumption (37–490 MJ/m^2) despite having a relatively low conversion efficiency (4–9%). OPVs use of materials with lower embedded energy and deployment of low cost deposition methods such as printing and roll-to-roll coating are responsible for its relatively low energy consumption and subsequent short EPBT [87]. DSSC reports a wide range for its EPBT values (0.69–52.30) with the highest recorded payback time (52.30). This is due to its relatively high upper band CED value (24007 MJ/m^2) and low conversion efficiency (10–12.3%). For DSSC cells where the cells are used to achieve semi-transparent facades (as a construction material), a comparatively high CED is expected. However, as its median EPBT is relatively low (2.26) it indicates that only a few scenarios have abnormally high CED values. Comparing EPBTs of the assessed thin film technologies with mono-Si and multi-Si, it can be seen that majority of them have a wider range than these established technologies. This is especially the case for emerging thin film solar cells as the maximum EPBT is often magnitudes higher than the minimum. PSCs, one of the most promising emerging thin film solar cell has EPBT values between 0.40 and 41.05. This is mainly due to the differences in the energy consumed by the various deposition methods selected within the system boundaries of the LCA studies. Spin coating is the deposition method deployed in majority of the LCA studies, however as it does not have the potential for scale up, LCA studies with spray [39], screen printing [88], slot die [89] and inkjet printing [68] have also been conducted. These various deposition methods invariable lead to differences in the assumptions made for loss of materials and solvent which can affect environmental results significantly. Another parameter that affect results is the use of different cathode materials with some studies electing to use precious metals such as gold and silver that have high embodied energy in comparison with carbon that has a lower embodied energy. The elimination of the hole transporting layer in some studies also aids the wide variance in EPBT values seen for PSCs.

All the analysed thin film solar cells except GaAs and its tandem were seen to have the possibility of EPBT lower than mono-Si and multi-Si if manufactured using relatively low CED whilst still generating cells with high efficiencies. This indicates that with the right combination of low embodied energy materials and process methods the assessed thin film solar cells have the ability to rival traditional silicon-based cells.

Variations in EPBT can be attributed to a variety of parameters, including the type of installation, the type of solar cells, and the various manufacturing methods deployed. For instance Ref. [36], assessed that EPBT is moderate for flat-roof installations and longest for facade solar cell systems, nearly two times longer than that of slanted-roof solar cell systems due to the energy requirements for these type of installations. EPBT values shown in Table 5 indicate that despite the fact that thin film solar cell modules generally require less energy to manufacture, their EPBT can be higher than crystalline silicon solar cell modules due to their lower conversion efficiency and, as a result, higher BOS requirements. It is worth noting that for thin film solar cells, the largest part of the CED comes from the soda lime glass used as substrate, rather than the active materials in the solar cell. Equally important, the double interest for the technology to go for alternative substrates such as polyamide or stainless steel; not only does it increase the range of application owing to the flexibility and light-weightiness, it also permits to forego the use of expensive glass and thus markedly lower the CED.

Table 5
Review of energy payback time (EPBT) for various commercial and emerging thin-film solar cell technologies.

Technology	PCE (%)	CED (MJ/m^2)	EPBT	Median EPBT
Commercial thin-film solar cells				
a-Si	9.5–12.24	862–1202	1.53–2.76	2.14
CIGS	12.7–20	1236–1936	1.35–3.32	2.11
CIS	10–13	1117–4334	1.87–9.44	3.90
CdTe	8.51–18.6	684–1971	0.8–5.05	2.18
GaAs	24.1–29	7674	5.77–6.94	6.35
GaAs Tandem	28–28.5	6437–8671	4.92–6.75	6.12
Emerging thin-film solar cells				
PSC	6.4–26.5	400–12060	0.40–41.05	3.60
PSC Tandem	6–27	419–5311	0.34–19.28	4.06
DSSC	10–12.3	391–24007	0.69–52.30	2.26
OPV	4–9	37–490	0.09–2.67	0.43
CZTS	10–12.6	–	–	–
QD	1.9–9.2	1030	2.44–11.81	7.12
Crystalline silicon solar cells				
Mono-Si	25	2860–5253	2.49–4.58	3.54
Multi-Si	23	2699–5150	2.56–4.88	3.72

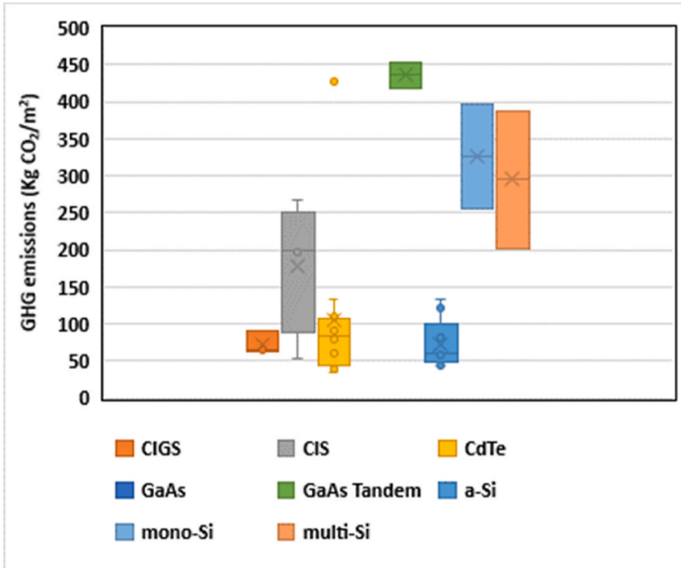
a-Si: amorphous silicon, CIGS: copper indium gallium selenide, CIS: copper indium selenide, CdTe: cadmium telluride, GaAs: gallium arsenide, PSC: perovskite solar cells, DSSCs: dye-sensitized solar cells, OPV: organic photovoltaics, CZTS: kesterites or copper zinc tin sulphide, QD: colloidal quantum dot, Mono-Si: mono crystalline silicon, Multi-Si: multi crystalline silicon

4.3. Environmental impacts of thin-film solar cells

This section presents the environmental impacts of the assessed thin-film solar cell technologies, covering the global warming potential impact category and other environmental impacts, depending on literature data availability.

4.3.1. GWP of thin-film solar cell systems

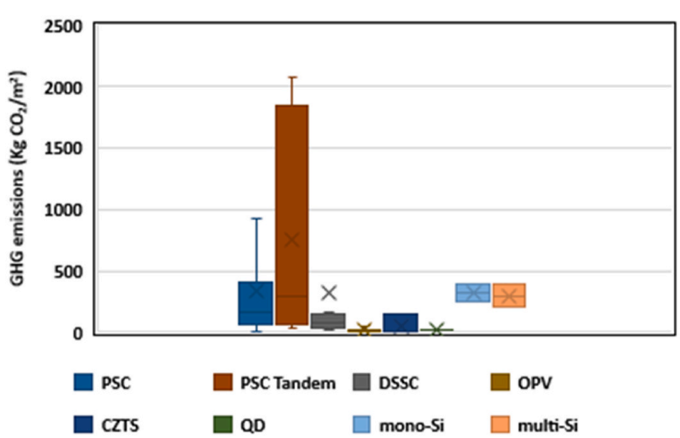
The GWP impact category was the most reported environmental indicator among the reviewed LCA studies, thus it was assessed separately in this study. Fig. 6 shows the GHG emission for commercial and emerging thin-film solar cells in comparison to crystalline silicone based ones. The GWP ranged from 33.41 to 428 kg CO_2-eq./m^2 (median: 81 kg CO_2-eq./m^2) for commercial thin-film solar cell technologies and between 0.57 and 2066 kg CO_2-eq./m^2 (median: 55.6 kg CO_2-eq./m^2) for emerging thin-film technologies. The differences were mainly attributed to the type of modules and the technology adopted during the manufacturing process. Among all assessed thin-film technologies, CZTS (median: 5 kg CO_2-eq./m^2) and OPV (median: 10 kg CO_2-eq./m^2) had relatively low environmental impact compared to others. Looking at median values of GaAs tandem cells (436.5 kg CO_2-eq./m^2) it can be seen that they generated the highest GHG emissions during their life cycle due to their higher energy requirements (7674 MJ/m^2) for solar cell manufacturing. This result is expected considering that GaAs fabrication processes rely on epitaxial deposition, which implies the use of a clean room and wafer substrates. An active field of research in the community aims at substituting the GaAs wafer by post-deposition lift-off ('epitaxial lift-off'), which can allow to reusing the wafer [90]. Such a method, if successful, would markedly reduce the global GHG emissions of GaAs-based devices. High GHG emissions was also observed for PSC tandem (286 kg CO_2-eq./m^2) due to the same facts. This is in line with what was observed by Leccisi and Fthenakis [42] as tandem PSC cells tend to have more GWP than single junction cells when normalised. However, due to their higher efficiencies they emit lower GHG to generate the same amount of electricity than their single junction counterpart [42]. Analysing single junction solar cells, CIS (198.68 kg CO_2-eq./m^2) and PSC (166 kg CO_2-eq./m^2) were found to emit the



	CIGS	CIS	CdTe
Median	65	199	83
	GaAs	GaAs Tandem	a-Si
Median	--	437	61
	Mono-Si	Multi-Si	
Median	326	295	

(a) Commercial thin-film solar cell technologies

	PSC	PSC Tandem	DSSC
Median	166	286	74
	OPV	CZTS	QD
Median	10	5	25



(b) Emerging thin-film solar cell technologies

Fig. 6. Review of global warming potential (GWP) of various thin-film solar cell technologies in comparison to the conventional Si-based technologies.

highest amounts of greenhouse gases. This could be attributed to the specific manufacturing processes and materials used in these solar cell technologies. On the other hand, mono-Si (325.51 kg CO_2-eq./m^2) and multi-Si (294.72 kg CO_2-eq./m^2) solar cell systems, which are based on crystalline silicon, exhibited poorer performance compared to single junction thin film cells. This can be attributed to the high-energy requirements associated with the production of these cells, as they typically involve more energy-intensive processes, such as the production of high-purity silicon and the formation of crystalline structures. The high-energy requirements and associated greenhouse gas emissions in mono-Si and multi-Si solar cell systems make them less environmentally friendly compared to single junction thin film cells. This highlights the importance of considering the energy efficiency and environmental impact of different solar cell technologies in order to make informed decisions in the transition towards sustainable energy systems.

[91] demonstrated that GHG emissions from thin film solar cell production can be reduced by 82% if conventional grid power were substituted with solar generated electricity or any other suitable

renewable energy resource. During the life cycle of solar cells, the majority of GHG emissions are connected to energy consumption [92]. Only steel and aluminium manufacture (for supports and frames) and silica reduction (for silicon solar cells) produced emissions unrelated to energy usage, but the total share is usually less than 10% [93]. [86] evaluated the environmental performance of six different types of solar cell modules, including mono-Si, multi-Si, a-Si, a-Si/mono-Si, CIS, and CdTe, using real equipment data and energy output findings. CIS and multi-Si solar cell were found to outperform other solar cells when results were not normalised. This is contrary to what is observed here as CdTe and a-Si performed better than CIS and multi-Si, highlighting the importance of removing the difference in lifetimes, performance ratio and efficiencies in reporting GWP results [86] results were attributed to higher efficiencies in CIS and multi-Si solar cell alongside reduced energy demand throughout its lifecycle.

Overall, GHG emissions results indicate that a-Si had the best environmental performance in comparison to other commercial thin-film technologies with CZTS and OPV performing better than other emerging thin-film solar cells. Large-scale solar cell projects should strive to deploy CZTS or OPV solar cells where possible as these were found to be the best performing thin film solar cells environmentally. It is worth noting that the conclusion related to CZTS was derived based on a limited number of existing studies. Hence, it is crucial that future researches concentrate on studying the environmental performance of CZTS to obtain a more comprehensive understanding of its sustainability.

4.3.2. *Other environmental impacts of thin-film solar cell systems*

The other reported environmental impact categories in the reviewed LCA studies of commercial and emerging thin-film solar cell technologies are demonstrated relative to the maximum value for each category in Fig. 7 (see supplementary information for raw data). The literature review of solar cell systems revealed several impact assessment methods and impact categories. Each method offers for the calculation of multiple impact categories (e.g., GWP, AP, etc.) expressed in terms of specific environmental indicators. Furthermore, each approach allows for the estimation of environmental indicators based on different assumptions (in terms of pollutants and characterisation parameters), which can lead to uncertainty in assessments because all options are possibly correct [20]. In addition, the reviewed LCA studies have adopted different key parameters (such as panel types, solar cell systems, area and module size, geographical locations, efficiencies, etc.), and methodological

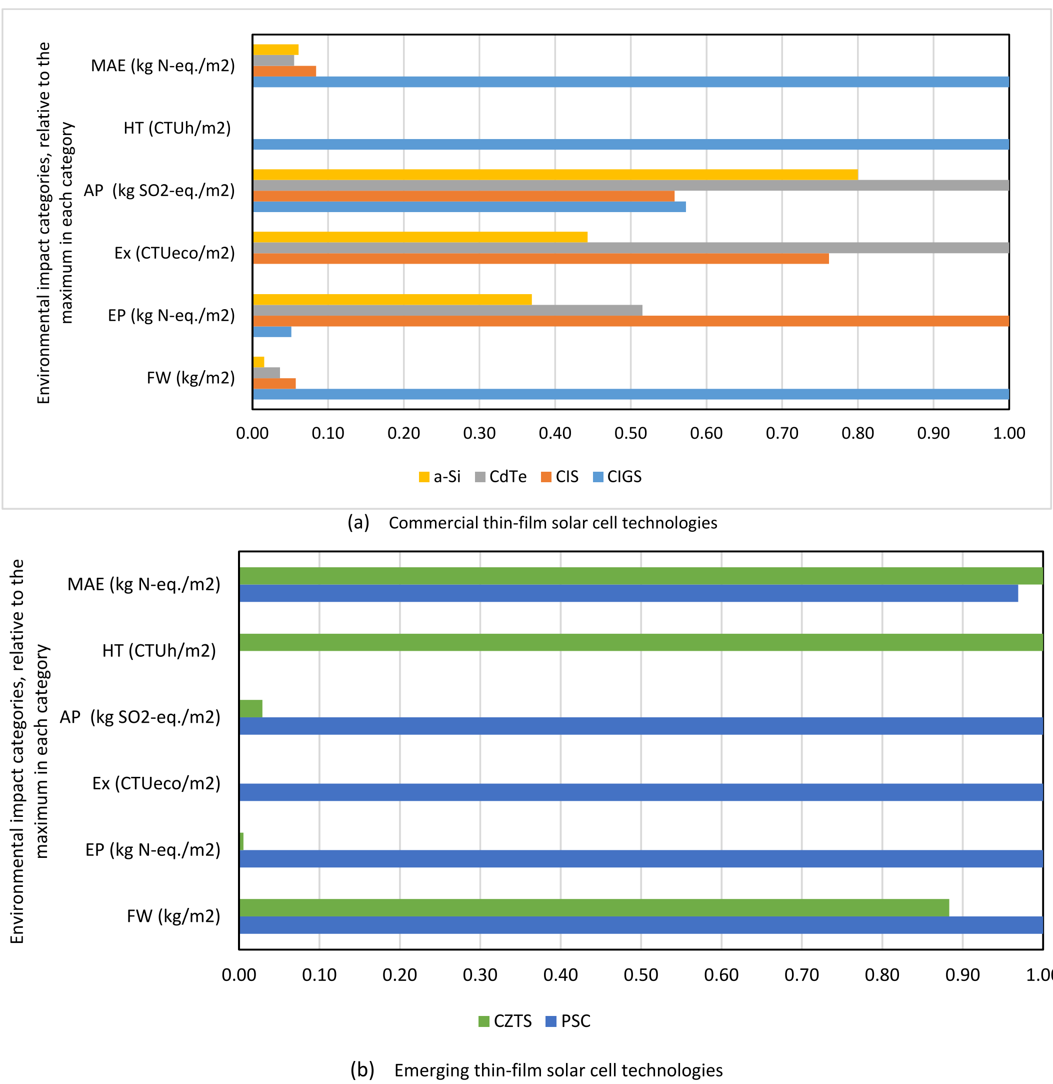


Fig. 7. Environmental impact of different thin-film solar cell technologies (Data are displayed relative to the maximum)
Raw data for CIS, CdTe, a-Si, and PSC adapted from Ref. [39] and data CIGS and CZTS adapted from Ref. [97] (see supplementary material for raw data)
Environmental impact categories: FW:Freshwater use; EP: Eutrophication potential; Ex: Ecotoxicity; AP: Acidification potential; HT: Human toxicity; and MAE: Marine Eutrophication.

aspects (such as functional unit, system boundaries, life cycle stages, impact categories, and impacts assessment methods). Moreover, there was a wide difference in the expression of results among these studies, whereby some results are presented in absolute values others were presented as normalised scores. All these factors rendered the comparison of the environmental impacts of the assessed thin-film solar cell technologies difficult. In this study, results were all converted to per m^2, to provide a common basis for comparison.

The new circular economy action plan adopted by the European Commission in 2020 emphasizes on the importance of considering a complete product's life cycle. It strives to reduce waste and keep materials utilised in the European Union (EU) economy for as long as feasible, targeting product designs that stimulates circular economy principles, and promotes sustainable consumption [94]. Although, LCA is recognized as well established tool suitable for assessing the environmental performance of a product' life cycle and the movement to a circular economy (CE), political initiatives focus on the path to CE without evaluating activities and targets using this tool [95]. Moreover, despite there being existing guidelines for LCA developed by the European Commission such as the ILCD handbook [96]and the International Energy Agency [75] LCA guideline for assessing the photovoltaic electricity. When assessing solar panel technologies, there is no consistency among the different LCA research activities on the use of methodology, especially in relation to the section of the environmental impact categories. Therefore, there is a need to standardize the LCA methodology among LCA practitioners and to promote life cycle thinking in business and policy making by focusing on underlying data and methodological needs.

Commercial thin-film solar cells are manufactured by the deposition of semiconductor layers on glass, plastic, or metal substrates. Cadmium, indium, gallium, tellurium, and copper are designed to make up the semiconductor layer. As previously stated in Section 3, these materials are less expensive compared to c-Si first generation solar cell technologies. The environmental impact of commercial solar cells has been studied as demonstrated in Fig. 7a, with promising potential for CIGS (except for MAE, FW and HT impact categories). Further studies assessing the environmental impacts of emerging thin-film technologies need to be conducted in the future.

5. Summary and conclusion

Life cycle assessment studies of six commercial thin-film solar cells (a-Si, CIGS, CIS, CdTe, GaAs and GaAs tandem) as well as six emerging thin film solar cells (PSC, PSC tandem, DSSC, OPV, CZTS, QD) were analysed in relation to three indicators (energy demand, energy payback time, and global warming potential) and compared with conventional crystalline silicon solar cell systems (mono-Si and multi-Si solar cells).

There was a considerable variance among previous LCA studies on thin-film solar cell technologies. For instance, the rates of the three evaluated indicators varied significantly depending on different influencing factors mainly, the type of solar cell and module, the processes and technologies adopted for manufacturing, the material configuration, the deposition method, the locations and weather conditions, and the methods used for estimation, etc. It is worth noting that the time at which a specific study was performed, would also play a key role in this context, as industrial processes have dramatically changed during the past two decades.

The review of previous LCA studies showed that emerging thin-film technologies performed better than commercial thin-film technologies. Life cycle energy requirement for emerging thin-film technologies ranged from 103 to 3546 MJ/m^2 (with a median of 1069 MJ/m^2) and EPBTs varied from 0.43 to 7.12 (with a median value of 1.34) years while the GWP was in the range of 5–286 $KgCO_2eq/m^2$ (with a median of 49 $KgCO_2eq/m^2$). In comparison, the life cycle energy requirement, EPBT and GWP of commercial thin-film solar cell technologies were in the ranges of 1054–7939 MJ/m^2 (with a median of 1716 MJ/m^2), 2.11–6.35 years (with a median value of 2.36), and 61–437 $KgCO_2eq/m^2$ (with a median of 74 $KgCO_2eq/m^2$), respectively. These differences were mainly stemmed from the energy and material required for manufacturing, which was more improved for emerging thin-film technologies.

Among the six types of emerging thin film solar cell systems, the perovskite (single-junction and multi-junction) solar cells had the highest environmental impact due to the highest amount of energy consumption despite having the highest efficiencies. Despite that, CZTS had the lowest environmental impact among the studied emerging thin-film technologies, previous studies did not address the life cycle energy demand during processing, and thus more studies are needed in this area. Meanwhile, QD had the longest EPBT due to its lower conversion efficiency; OPV had the shortest EPBT due to its lower energy demand and relatively high conversion efficiency. Overall, OPV solar cell system performed better than her counterparts emerging thin-film technologies did.

For commercial thin-film technologies, GaAs tandem consumed the largest amount of primary energy, and GaAs (single junction) had the longest EPBT, which can be attributed to its extremely high energy demand. In relation to GHG emission rates, GaAs tandem thus generated the highest GHG emissions during its life cycle because of the high-energy intensity of the processes to produce the solar cells. As of now, GaAs application is restricted to military application due to the availability of space and funding. The a-Si had the lowest energy requirement and thus had the lowest environmental impacts. It equally possessed a very low EPBT due to its lower energy requirement and relatively high conversion efficiency. It is worth noting, that CIGS, performed very closely to a-Si, in relation to the life cycle energy demand and global warming potential, and had a shorter EPBT due to higher conversion efficiency.

Although, thin film solar cell systems had lower conversion efficiencies than crystalline silicon solar cell systems, they utilise less raw material and energy over their lifetime due to their comparatively simple manufacturing processes. As a result, improved CED, EPBT and GHG emission performance was expected. This is indeed the case for CED and GWP, as overall, the energy requirement of thin-film solar cell technologies is much lower than conventional crystalline silicon solar cell systems. This in turn led to less GHG emissions from thin film solar cells than silicon-based cells. Even though thin film solar cell modules generally require less energy to manufacture, their EPBT tend to be higher than crystalline silicon solar cell modules due to its lower conversion efficiency and, as a result, higher BOS requirements. Overall, crystalline silicon solar cells (mono-Si and multi-Si) had higher power conversion efficiency than thin-film solar cells, with mono-Si having an efficiency of 19–22% and 15–18% for multi-Si. GaAs and GaAs Tandem thin-film solar cells, had higher efficiencies of 26.55% and 28.25%, respectively.

The estimated findings of life cycle energy demand, EPBT, and GHG emission rates of thin-film solar cell systems were influenced by different factors. The addition of different alternative substrates (such as polyamide, stainless steel) are important levers to reduce costs, energy consumption and emissions.

The collected studies were evaluated based on the extent to which they covered the solar cell life cycle, and the variety of environmental impact categories considered. The review showed that there are some limitations in previous LCA studies on thin-film solar cells, such as significant differences in energy requirement estimation, inaccurate accounting of material-embodied energy and direct process-energy, etc. All these limitations would eventually lead to a significant amount of uncertainty in predicting the EPBT and GHG emission rates of any solar system. Other methodological limitations were also identified in this study including the lack of coverage of different life cycle stages and impact categories. In addition, most of these studies were applied in the context of developed economies neglecting developing economies highlighting the need for LCA practitioners to enhance their practice in relation to the identified shortcomings of the existing studies.

In summary, thin-film solar cell technologies have demonstrated to be environmentally advantageous and sustainable in terms of EPBT and GHG emission rates. Due to their lower life cycle energy demand and relatively higher conversion efficiency, a-Si, CIGS, and OPV solar cell technologies provide the best environmental benefits, such as the shortest EPBT and lowest GHG emission rate, among the twelve common types of commercial and emerging thin-film solar cell technologies. Both multi-junction GaAs and PSC provide the worst environmental benefits, due to their relatively higher-energy requirement for solar cell production. In addition, advanced CZTS systems demonstrate good environmental performance, yet more studies are needed in this area to assess its energy demand and impacts.

This paper highlights the potential of thin film solar cells to reduce energy consumption and subsequently environmental burdens. Further increase in efficiencies of these cells could potentially reduce the EPBT to rival that of mono-Si and multi-Si solar cells.

Credit authors statement

Amani Maalouf: Writing – original draft, Conceptualization, Software, Methodology, Formal analysis, Data curation, Writing – review & editing. **Tobechi Okoroafor**: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation. **Zacharie Jehl**: Validation, Review, Data curation. **Vivek Babu**: Validation, Review, Data curation. **Shahaboddin Resalati**: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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

Supplementary Materials included with the submission.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No 952982 and No 869898.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113652.

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