



Ecodesign perspectives of thin-film photovoltaic technologies

A review of life cycle assessment studies

Chatzisideris, Marios Dimos; Espinosa Martinez, Nieves; Laurent, Alexis; Krebs, Frederik C

Published in:

Solar Energy Materials & Solar Cells

Link to article, DOI:

[10.1016/j.solmat.2016.05.048](https://doi.org/10.1016/j.solmat.2016.05.048)

Publication date:

2016

Document Version

Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):

Chatzisideris, M. D., Espinosa Martinez, N., Laurent, A., & Krebs, F. C. (2016). Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies. *Solar Energy Materials & Solar Cells*, 156, 2-10. <https://doi.org/10.1016/j.solmat.2016.05.048>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies

Marios D. Chatzisideris,¹ Nieves Espinosa,¹ Alexis Laurent² and Frederik C. Krebs^{*,1}

¹ *Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark*

² *Division for Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark*

e-mail: frkr@dtu.dk

Abstract

Here, we review 33 life cycle assessment (LCA) studies of thin-film photovoltaic (PV) technologies that have had a holistic coverage in their assessments and/or have included ecodesign aspects. Only five of them were found to have a comprehensive life cycle and impact coverage, and their analyses highlighted the importance of (i) including the entire life cycle of the PV system, in particular the often-omitted disposal stage, and (ii) assessing all relevant impact categories and not just climate change or energy requirements to minimise the risk of burden-shifting. Out of the 28 studies embracing ecodesign considerations in parts of the PV life cycle, the analysis of the eleven of them addressing primary energy demand during module production suggests that electricity consumption during the metal deposition processes is a top contributor and should be prioritised by PV technology developers. A similar analysis of the ten studies having included the balance of system components (BOS) in the assessments showed that these contribute significantly to most environmental impact categories. Beyond recommending that stakeholders in the PV field rely on LCA to support decision-making and to guide scientific research and technological development, we strongly advocate LCA practitioners to include the entire PV system, including the BOS, to identify ecodesign opportunities without risking potential burden-shifting across the different parts of the system and across impact categories.

Keywords: eco-design; life cycle assessment; photovoltaics; thin film

1. Introduction

Low-carbon energy technologies are essential to support climate change mitigation strategies and address rapid growth of global electricity demand. According to the International Energy Agency's (IEA) BLUE Map

scenario, wide-scale deployment of low-carbon technologies is needed in order to meet electricity demands in 2050 while cutting greenhouse gas (GHG) emissions from power generation by 76% compared to 2007 [1]. Renewable energy sources are expected to contribute significantly to this effort with the BLUE Map scenario suggesting an increase in the combined share of solar, wind and hydropower from 16.5% of total electricity generation in 2010 to 39% in 2050. With respect to photovoltaics (PV), the global installed capacity of 135 GW in 2013 is envisioned to rise to 1721 GW by 2030 and 4674 GW by 2050 according to the High Renewables scenario planned by the IEA in its 2014 technology roadmap for solar photovoltaic energy [2]. These projected PV installed capacities could profitably be integrated onto building structures, where they could form mini-grids and sustain self-production and self-consumption. In particular, a deployment in urban areas not only onto residential buildings but also onto other types of buildings, e.g. offices or supermarkets, could bring a good match between the demand and the daytime supply of electricity [3].

In Europe, which has pioneered the deployment of photovoltaics, PV technologies are expected to contribute to the European Union's (EU) energy efficiency targets by improving the energy performance of the building sector (Directive 2012/27/EU). There is a growing consensus that building-integrated photovoltaic (BIPV) systems will play a major role for achieving EU's target for nearly zero-energy buildings (NZEB) [4]. In addition to generating electricity, BIPV systems perform building envelope functions by replacing building elements, e.g. windows, tiles, shingles and blinds. It is therefore important to account fully for these multi-functionalities when estimating financial and environmental costs and benefits. In this regard, a distinction between wafer-based and thin-film PV technologies is necessary as the latter presents significant advantages over the former in BIPV applications, such as lower weight and lower installation costs as well as improved flexibility and optical semi-transparency [5,6].

In that context, it is important to ensure that such development and deployment of the PV technologies be made with as low environmental impacts as possible [7,8]. A number of studies have thus warned against risks posed by the global deployment of PV systems at the terawatt scale of installed capacity, e.g. the pressure on critical materials like rare earth metals from different solar cell technologies [6,9–11]. To address these environmental problems in a holistic manner, life cycle assessment (LCA) can be used. LCA is a decision-support tool that enables the quantification of all relevant environmental impacts throughout a system's life cycle from raw materials extraction through manufacturing and use/operation of the system up to its end-of-life, according to ISO 14040/14044:2006 standards [12,13]. It is conducted iteratively through four phases: goal and scope definition; life cycle inventory (LCI) analysis; life cycle impact assessment (LCIA); and, interpretation [13]. LCA has been widely used for investigating the environmental impact of PV technologies, and LCA practitioners were recently provided with methodological guidance issued by the IEA [14]. Until now, LCA applications to PV technologies have mainly had two purposes: (i) to document environmental performances of specific technologies and compare them to other renewable and non-renewable energy systems; and (ii) to identify environmental hotspots and guide scientific research and technological development.

The ecodesign of energy-related products is a crucial factor in the EU strategy on Integrated Product Policy (Directive 2009/125/EC). It is seen as an effective tool to improve energy efficiency as well as support industrial competitiveness and innovation by promoting the better environmental performance of products throughout the Internal Market. According to the Directive, ecodesign of energy-related products such as PV modules is defined as the 'integration of environmental aspects into product design with the aim of

improving the environmental performance of the product throughout its whole life cycle'. The current work relates to the latter purpose of utilising LCA as a tool for ecodesign, with a focus on BIPV applications and thus thin-film PV systems.

Until now, most review papers of LCA studies covering thin-film PV technologies have limited their focus to collecting results on GHG emissions and energy-related indicators such as cumulative energy demand (CED) and energy payback-time (EPBT), and comparing performances among different PV and renewable technologies [15–23]. Table S.1 illustrates those limitations, also in relation to the technological scope and thin-film PV coverage. Only a few review papers go beyond this scope, and consider other environmental impact categories (LCA term for classes representing environmental issues of concern e.g. climate change, land use, resource depletion) [24–27] or examine contributions of specific system components to the total environmental burden [28,29].

Overall, existing review papers lack a systematic consideration of all possible environmental issues (beyond climate change), and an explicit description of which processes or parts of the PV life cycle were considered by the LCA studies under review. These considerations are critical within the LCA methodological framework. Only by considering all environmental impact categories and the entire PV life cycle, including the often-omitted disposal stage, the shifting of a potential environmental burden from one life cycle stage to another or from one environmental problem to another can be identified and possibly avoided [12]. Otherwise, potential trade-offs might be missed, and environmental burden-shifting might take place, e.g. focusing on reducing GHG emissions while inadvertently increasing other nonetheless relevant impacts [30]. Examples of such relevant impacts include damages to ecosystems and human health caused by emissions of toxic substances or metal depletion, e.g. rare earth metals [31–33]. Finally, most review papers in the scientific literature lack an ecodesign perspective, where the identification of the so-called environmental hotspots, i.e. life cycle stages, system components or processes where the largest impacts stem from, are rarely associated with ecodesign recommendations relevant to PV technology developers.

The purpose of this study is therefore to address these gaps. Taking all studies addressing relevant impact categories throughout the entire life cycle of the PV systems, including the often-omitted disposal stage, we aim to investigate how results of past LCA studies of thin-film PVs can be used to identify bottlenecks and opportunities for technological improvement and mitigation of environmental impacts. Also, by identifying and critically reviewing ecodesign aspects of LCA studies across thin-film technologies, we aim to highlight the value of using LCA as a strategic decision-support tool to guide scientific research and technological development [31], and not just document the environmental performance of the system under study. The intended audience of our work includes both thin-film PV technology developers and LCA experts. We believe that effective ecodesign of thin-film PV requires a collaborative effort and expertise in both fields, according to international standards of environmentally conscious design for electrical and electronic products that stipulate that “environmentally conscious design requires collaboration and contributions of all stakeholders along the supply chain” [34].

2. Methods

2.1. Technological scope

The review scope includes LCA studies of thin-film photovoltaic technologies suitable for building integration, and excludes concentrated PV systems and product-integrated PVs. Studies that examined multifunctional

systems with combined results such as green roofs, solar houses, and water desalination systems were deemed outside the scope of this study and were thus disregarded. Thin-film photovoltaic technologies include commercial technologies, cadmium telluride (CdTe), copper indium gallium diselenide (Cu(In, Ga) Se₂ or CIGS), as well as amorphous and nanocrystalline silicon (a-Si and nc-Si); and, emerging technologies, copper zinc tin sulphide (Cu₂ZnSnS₄ or CZTS), zinc phosphide (Zn₃P₂), perovskite solar cells (PSC), organic photovoltaics (OPV), dye-sensitized solar cells (DSSC), quantum dot photovoltaics (QDPV), and gallium arsenide (GaAs) were included as thin-film despite requirement for wafers as templates for crystal growth [6].

2.2. Collection of studies

Only scientific journal papers written in English and published from 2000 and onwards were considered in the review. A screening step using the Scopus database (<http://www.scopus.com/>) was used and complemented by a check for citing and cited papers of all relevant papers with case studies and reviews of LCA applied to thin-film PV (see also Table S.1). An additional screening step was made using Google Scholar (<https://scholar.google.com/>) to identify more recent literature published until mid-2015.

2.3. Analysis and classification of studies

The collected studies were evaluated with respect to the extent of their coverage of the PV life cycle, the range of the included environmental impact categories, and the inclusion of eco-design recommendations. The studies were grouped in two sets described below.

Set 1 comprises LCA studies that cover the entire PV life cycle, and include more than one impact category. Figure 1 illustrates the system boundaries of the entire PV life cycle (cradle to grave) used as reference in the review. It encompasses the production stage with all upstream processes, including the resource extractions; the use stage including the installation and operation with balance of system components (BOS) such as inverters, wiring and support structures; and, the end-of-life stage covering decommission and waste management of all materials, including potential recycling. Capital infrastructure, labour work and maintenance have been excluded.

With respect to the impact categories, these include: climate change (CC); ozone depletion (OD); photochemical ozone formation (POF), acidification (A); eutrophication (E); terrestrial eutrophication (TE); freshwater eutrophication (FE); marine eutrophication (ME); freshwater ecotoxicity (FEC); terrestrial ecotoxicity (TEC); human toxicity (HT); human toxicity, cancer effects (HTC); human toxicity, non-cancer effects (HTnC); respiratory inorganics (RI); ionising radiation, human health (IR); land use (LU); agricultural land occupation (ALO); urban land occupation (ULO); natural land transformation (NLT); water resource depletion (WD); resource depletion (RD); metal depletion (MD); fossil depletion (FD); and, solid waste (SW).

In addition to the above, although CED is not an environmental impact assessment category in LCA terms (i.e. energy consumption is not an environmental problem per se), it was regarded as one for the analysis of the studies, as explained next. Although LCIA methodological uncertainties should be considered, CED results have been shown to correlate well with a number of impact categories, including climate change, resource depletion, acidification, eutrophication, photochemical ozone formation, ozone depletion and human toxicity, when assessing the environmental performance of energy production [35].

Set 2 has no requirements with respect to the PV life cycle coverage or the environmental impact coverage of the studies, and comprises all LCA studies with ecodesign aspects, i.e. studies where authors have used their results in order to draw conclusions and make recommendations for further research and development of thin-film PV technologies. Set 2 can thus be overlapping with Set 1, provided that studies meet the criteria for Set 1 and include an ecodesign focus.

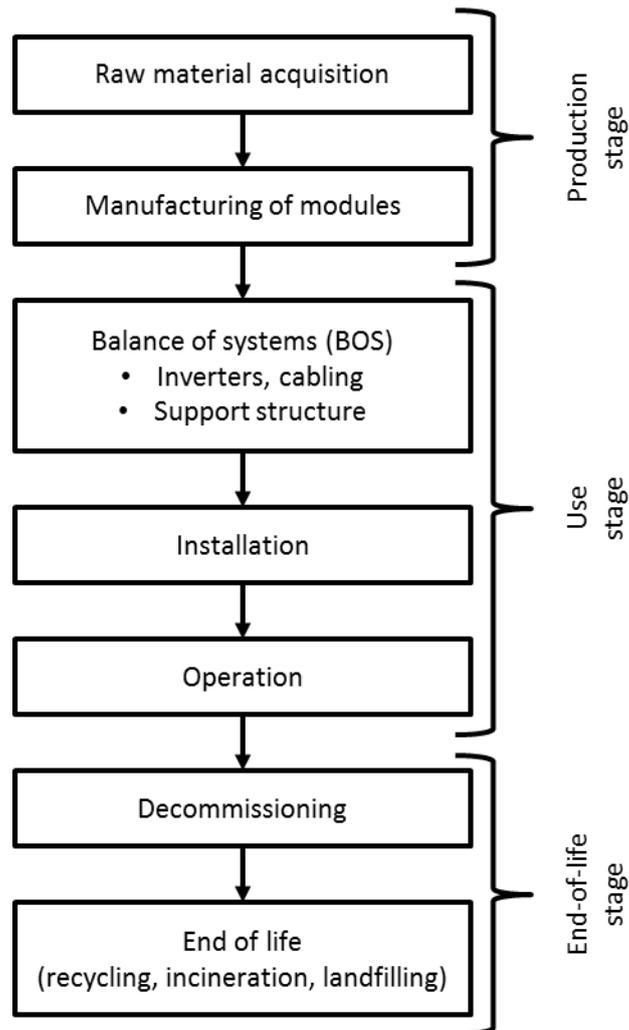


Figure 1. System boundaries of a complete PV life cycle (cradle to grave) as considered in this work: production stage with all upstream processes; use stage including installation and operation with balance of system components (BOS) such as inverters, wiring and support structure; and, end-of-life stage covering decommissioning and waste management of all materials.

2.4. Interpretation of study findings

Set 1 was quantitatively analysed to examine (i) the influence of including the entire life cycle, in particular the disposal stage, in the overall environmental burden, and (ii) the importance of covering all relevant environmental impact categories to avoid burden-shifting.

Set 2 was investigated to identify (i) important impact categories to consider in LCA studies of thin-film photovoltaics, (ii) hotspots of primary energy demand (PED) at the module level, and (iii) contributions of BOS components to environmental burden. Important impact categories were identified by checking whether the studies produced normalised LCA results (and assuming equal weighting among impact categories). In LCA context, normalisation is performed to better understand the relative magnitude of each of the environmental impact results of the system under study, by putting them in perspective with a reference situation e.g. impacts associated with the territorial activities of a given region [13]. In practice, normalisation transforms each environmental impact indicator score by dividing it by a corresponding reference value, the so-called normalisation reference, which reflects the average impact of that reference system over a period of time, e.g. annual contribution of an average person in the world to each of the impact categories [36].

3. Results and Discussion

3.1. Collected LCA studies of thin-film PVs

A total of 46 papers with LCA studies of thin-film technologies were collected, and a total of 31 studies were identified as fulfilling the criteria for Set 1 and/or Set 2 – see Table 1. Fifteen studies were thus disregarded; these are documented in Table S.2, available in the Supporting Information.

Commercial technologies CdTe, CIGS and thin-film Si along with the emerging organic photovoltaics (OPV) were largely represented with 11-16 studies per technology (Table 1). Emerging technologies like DSSC, GaAs and QDPV were less represented with 2-4 studies per technology. The rapidly evolving technology of perovskite solar cells is also included with two recently published studies. Overall, the number of studies has increased significantly with two thirds of them published in the period 2011-2015. With regard to LCIA, Eco-indicator 95/99 [37], CML [38] and ReCiPe [39] were the most commonly used LCIA methodologies among the collected LCA studies.

As Table 1 shows, only five out of the 46 total collected studies fulfil criteria for Set 1, thus indicating that there is a strong need for practitioners to improve their practice when applying LCA both in terms of the life cycle stage and the impact coverage (see Section 3.2). A number of 28 studies were found to consider ecodesign aspects, and thus fulfil criteria for Set 2, where OPV technology dominates with 11 studies. Analyses of the 31 studies meeting Set 1 and Set 2 criteria are addressed in the subsequent sections.

In the following, results are not distinguished among the various thin-film PV technologies based on maturity level, as we try to present a holistic view of the thin-film PV field, and because there was not always a sizeable sample of LCA studies per technology for a consistent analysis across the paper. Nevertheless, we specify the type of thin-film PV technology, both in text and all the tables, to render our findings more transparent.

Table 1

Retrieved LCA studies of thin-film PV technologies differentiated into the 2 predefined sets (total of 33 studies).

LCA study	Publication year	Thin-film technology	Life cycle stage coverage ^a			Multi-impact assessment coverage ^b	Ecodesign aspects ^c
			Production	Use	End of life		
Set 1 – Full life cycle and multi-impact assessment coverage (5 studies)^d							
Held and Ilg [40]	2011	CdTe	●	●	●	●	●
Carnevale et al. [41]	2014	CdTe, CIS	●	●	●	●	○
Serrano-Luján et al. [42]	2015	CdTe	●	●	●	●	○
Ng and Mithraratne [43]	2014	a-Si, a-Si/nc-Si	●	●	●	●	○
Espinosa et al. [31]	2015	OPV	●	●	●	●	●
Set 2 – Ecodesign considerations (28 studies)^d							
Kato et al. [44]	2001	CdTe	●	●	○	○	●
Raugei et al. [45]	2007	CdTe, CIS	●	●	○	●	●
Kim and Fthenakis [46]	2011	a-Si, a-Si/nc-Si	●	○	○	○	●
van der Meulen and Alsema [47]	2011	a-Si, a-Si/nc-Si	●	●	●	○	●
Held and Ilg [40]	2011	CdTe	●	●	●	●	●
Mohr et al. [48]	2013	a-Si/nc-Si	●	●	○	●	●
Kim et al. [49]	2014	CdTe	●	●	○	○	●
Bergesen et al. [50]	2014	CdTe, CIGS	●	●	○	●	●
Collier et al. [51]	2014	CdTe, CIGS, CZTS, Zn ₃ P ₂	●	○	○	●	●
Espinosa et al. [52]	2015	Perovskites	●	○	○	●	●
Gong et al. [53]	2015	Perovskites	●	○	●	●	●
Roes et al. [54]	2009	OPV	●	●	○	●	●
Garcia-Valverde et al. [55]	2010	OPV	●	○	○	○	●
Espinosa et al. [56]	2011	OPV	●	○	○	○	●
Espinosa et al. [57]	2012	OPV	●	○	○	○	●
Espinosa et al. [58]	2012	OPV	●	○	○	●	●
Emmott et al. [59]	2012	OPV	●	○	○	○	●
Anctil et al. [60]	2013	OPV	●	○	○	○	●
Espinosa and Krebs [61]	2014	OPV	●	○	○	●	●
Espinosa et al. [62]	2014	OPV	●	●	○	●	●
Søndergaard et al. [63]	2014	OPV	●	○	●	●	●
Espinosa et al. [31]	2015	OPV	●	●	●	●	●

M.D. Chatzisideris, N. Espinosa, A. Laurent, F.C. Krebs, Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies, Sol. Energy Mater. Sol. Cells. 156 (2016) 2–10. doi:10.1016/j.solmat.2016.05.048.

Greijer et al. [64]	2001	DSSC	●	○		○	●
Parisi et al. [65]	2014	DSSC	●	●	○	●	●
Şengül and Theis [66]	2011	QDPV	●	●	○	●	●
Meijer et al. [67]	2003	GaInP	●	○	○	●	●
Mohr et al. [68]	2007	GaAs, GaInP/GaAs	●	○	○	●	●
Mohr et al. [69]	2009	GaInP/GaAs	●	●	○	●	●

^a Life cycle stage coverage: (●) = included in the study; (○) excluded from the study or not transparently reported (not sufficiently to assess life cycle coverage).

^b Multi-impact assessment coverage: (●) = at least two impact categories considered; (○) less than two (including none if only emissions considered).

^c Ecodesign aspects: (●) = interpretation of LCA results for guiding research and technological development; (○) no ecodesign aspects.

^d See section 2.3 for classification of studies into Set 1 and Set 2.

3.2. Importance of full life cycle and multi-impact coverage

This section examines the five studies matching Set 1 criteria to determine (i) the influence of including the entire PV life cycle, particularly the disposal stage, on the LCA results across impact categories, and (ii) the importance of covering the whole spectrum of environmental impacts. Out of these five studies, two of them cover CdTe, one study addresses both CdTe and CIS, one thin-film Si and one OPV technologies. They embrace installed systems across Europe as well as Singapore and China. Among them, two studies describe existing systems, and two refer to BIPV systems.

Taking the five studies from Set 1, and quantifying the influence of the disposal stage on the LCA results of each system, it is observed that an LCA study might produce considerably different results for some impact categories if it disregarded the disposal stage – see Table 2. For example, taking the study by Espinosa et al. [31] and recalculating the LCA results of an OPV system excluding the disposal stage (recycling scenario), the original LCA results, which included the disposal stage, were found to be significantly lower. With the exception of respiratory inorganics impacts, which were higher by 51%, the original LCA results were observed to be lower than the recalculated results by 36-91% in the 15 considered impact categories (see Table 2).

These findings demonstrate the risk of bias in the LCA results when studies omit the disposal stage, and the severe implications for PV technology developers, as highlighted below. Most importantly, when omitting the disposal stage (or any part of the PV life cycle) the shifting of environmental burden between life cycle stages cannot be identified, and thus prevented, e.g. when PV technology developers take measures to reduce environmental impacts during the production stage, and might inadvertently increase environmental impacts in the disposal stage. In addition, if an LCA study disregards the disposal stage of the PV system, there are no opportunities to assess possible decreases of environmental impacts e.g. by considering recycling instead of landfilling or incineration, as shown above [31]. Unfortunately, the disposal stage is nearly systematically dismissed in LCA studies of thin-film PVs, as illustrated in the overviews of studies in Set 2 (Table 1) and disregarded studies (see Table S.2).

It is therefore strongly recommended that future studies should include this stage and a fortiori should include the entire PV life cycle to ensure that the conclusions and support provided to stakeholders are reliable. In cases where modelling of the system's end-of-life is a challenging task especially for emerging technologies where data might be scarce or non-existing [51,52,65], a number of studies can provide guidance for LCA practitioners on how to handle such a prospective approach, and how to account for uncertainties, e.g. by use of sensitivity scenarios [70,71].

Table 2

Importance of complete life cycle coverage (4 studies).

LCA study	Technology [scenario]	Impact results ^a (%)																
		PED	CC	OD	POF	A	E			FEC	HTC	HTnC	RI	IR	LU	WD	RD	SW
								FE	ME	TE								
Results including end of life compared to results excluding end of life																		
[40]	CdTe	-	97	-	95	96	94			-	-	-	-	-	-	-	-	-
[31]	OPV [recycling]	-	64	9	47	43	-			32	40	31	151	59	34	47	28	-
	OPV [incineration]	-	94	64	95	94	-			100	99	100	198	107	78	71	100	-
[43]	a-Si, a-Si/nc-Si	gr ^b	-	-	-	-	-			-	-	-	-	-	-	-	-	-
Results with end-of-life recycling compared to results with end-of-life landfilling																		
[41] ^c	CdTe	101	102	101	101	102	99			-	150	94	102	-	-	-	-	10
	CIS	102	102	103	102	103	103			-	249	113	105	-	-	-	-	9
[42]	CdTe [BIPV]	98	95	-	-	-	-			-	-	-	-	-	-	-	-	-
	CdTe [ground-mounted]	94	93	-	-	-	-			-	-	-	-	-	-	-	-	-

^a See Section 2.3 for description of impact categories.

^b Graphical representation of results is provided but numerical data are not available.

^c The authors do not report characterised impact results stemming from the PV life cycles (except for SW); instead, they present scores with negative values reflecting the avoided impacts compared to the Italian electricity generation mix.

Equally important to considering the entire PV life cycle, LCA studies must include all environmental impact categories to identify the most problematic ones, and avoid burden-shifting from one impact category to another e.g. decreasing the climate change impacts from greenhouse gas emissions while increasing other nonetheless relevant impacts such as impacts exerted by toxic emissions or metal depletion [30]. Revisiting the studies of Set 1, Table 3 presents comparisons of different analysed scenarios in each LCA study to show how LCA studies fail to capture possible positive or negative effects on other environmental problems, when they limit their scope of impact assessment categories to climate change. The empty cells of Table 3 illustrate how the decision of LCA practitioners and PV technology developers to focus on climate change impacts, in essence, effects a disregard for potential impact of the PV system on other environmental problems. Two illustrative examples from Table 3 are given below.

For example, Serrano-Luján et al. [42] compare the environmental impacts of two CdTe PV systems with that associated with Spain's average electricity mix, and find them lower by ca. 60-90% for 9 categories (see Table 3). In contrast, metal depletion impact results for those two systems are found to be higher than the impact results of Spain's average electricity mix. The authors tracked the causes of such increase to the high use of copper, lead and steel for the CdTe modules and the BOS structure [42].

Likewise, in the study by Ng and Mithraratne on thin-film Si systems [43], when the authors examine a scenario of moving module manufacturing from Japan to Singapore, PED decreases by 36%, while climate change impacts increase by 9% – see Table 3. The authors attribute the decrease of energy consumption to elimination of transport needs, and the increase of climate change impacts to the higher GHGs emission rate of Singapore's electricity mix compared to that of Japan's [43]. Therefore, GHGs emissions increase in total even though energy consumption decreases, in contrast to what one might expect. However, effects on other impact categories, either positive or negative, cannot be ascertained since the authors only consider PED and CC.

These findings highlight the importance of multi-impact coverage beyond climate change or energy-related indicators, which a large number of studies only consider in their assessments (18 out of the total 46 collected studies in this review – see Set 2 in Table 1 and Table S.2 in SI). Therefore, researchers and technology developers in the field of photovoltaics are recommended to encompass all impact categories to identify possible trade-offs, and provide adequate support to stakeholders such that decisions can be taken on an informed basis.

Table 3

Importance of multi-impact coverage (5 studies).

LCA study	Technology [scenario]	Impact results ^a (%)																			
		PED	CC	OD	POF	A	E			FEC	HTC	HTnC	RI	IR	LU			WD	RD		SW
							FE	ME	TE						ALO	ULO	NLT		MD	FD	
[40] ^b	CdTe	-	4	-	3	2	3			-	-	-	-	-	-			-	-		-
[41] ^c	CdTe	101	102	101	101	102	99			-	150	94	102	-	-			-	-		10
	CIS	102	102	103	102	103	103			-	249	113	105	-	-			-	-		9
[43] ^d	a-Si [scenario 2]	64	109	-	-	-	-			-	-	-	-	-	-			-	-		-
	a-Si/nc-Si [scenario 2]	45	25	-	-	-	-			-	-	-	-	-	-			-	-		-
	a-Si/nc-Si [scenario 2]	47	28	-	-	-	-			-	-	-	-	-	-			-	-		-
	a-Si/nc-Si [scenario 2]	46	27	-	-	-	-			-	-	-	-	-	-			-	-		-
	a-Si [scenario 2]	56	-	-	-	-	-			-	-	-	-	-	-			-	-		-
	a-Si [scenario 2]	81	-8	-	-	-	-			-	-	-	-	-	-			-	-		-
[42] ^e	[Spain's el. mix]	-	100	100	100	100	100	100	100	-	-	-	-	-	100	<10	100	100	<40	100	-
	CdTe [BIPV]	-	<20	<10	<20	<20	<90 <30 <40			-	-	-	-	-	<100	<10	<20	<30	100	<20	-
	CdTe [ground-mounted]	-	<20	<10	<20	<20	<90 <20 <30			-	-	-	-	-	<90	100	<10	<20	<90	<10	-
[31] ^f	OPV [incineration]	-	147	711	200	219	-			310	244	327	132	213	234			152	352		-
	OPV [PVC]	-	72	96	88	93	-			99	92	62	89	98	99			167	100		-

^a See Section 2.3 for description of impact categories.

^b Results are compared to impacts associated with Portugal’s electricity mix.

^c Results with end-of-life recycling are compared to results with end-of-life landfilling. The authors do not report characterised impact results stemming from the PV life cycles (except for SW); instead, they present scores with negative values reflecting the avoided impacts compared to the Italian electricity generation mix.

^d Results are compared to base case scenario and original manufacturing location (module 1: Japan, module 2, 3, 4 and 6: Taiwan, and module 5: Germany). For scenario 2, all modules are manufactured in Singapore i.e. eliminating transport and assuming Singapore’s electricity mix.

^e Results of BIPV and ground-mounted systems are compared with impacts associated with Spain’s electricity mix. The authors present graphical results, not numerical data, thus results are indexed, here, to highest result for every category, and presented with approximate values (<).

^f Results for the ‘incineration’ scenario are compared to the baseline scenario which assumes end-of-life recycling. Results for the ‘PVC’ scenario represent a choice of PVC as insulation material compared to baseline scenario with PET insulation material.

3.3. LCA studies with ecodesign aspects

This section examines Set 2, which comprises studies providing insights into ecodesign aspects – see Table 1. Tables S.3 – S.9 in Supporting Information, which are grouped by technology, present further details of the studies including a brief summary of their key findings. It shall be mentioned that the analyses of these studies in the following subsections are associated with important uncertainties due to the fact that many of them do not encompass full coverage of neither the life cycle of the systems nor the relevant environmental impacts. As demonstrated in Section 3.2, such malpractice might lead to biased results and hence not reliable conclusions (see Section 3.2).

3.3.1. Important impact categories for thin-film PV

As explained in Section 2.4, normalisation can provide useful support for interpreting and communicating the results of an LCA study [36]. For example, in the context of electricity generation, Laurent et al. [8] have presented a ‘sectorial normalisation’ approach that takes LCA results of electricity generation at the global scale as normalisation references. This approach can be used to identify which environmental impacts are higher than the global electricity generation average, and should be prioritised by technology developers [8].

Taking Set 2 and screening it for studies that performed normalisation of impact results, 10 studies were identified [31,50,52,58,61–63,65,67,68]. Assuming equal weighting of the impact categories, toxic impacts and resource depletion tend to dominate the impact results. All these LCA studies, with the exception of Bergesen et al. [50], perform normalisation based on the normalisation step integrated in the LCIA method used, i.e. using normalisation references provided by the method developer. Bergesen et al. [50] take the impacts associated with the average 2010 US electricity mix as a normalisation reference, which is comparable to the approach applied by Laurent et al. [8].

However, in spite of such relatively wide application, caution is needed when interpreting normalised results. Because of an incomplete coverage in LCIs and LCIA methods of the thousands of chemicals potentially being released to environment as a result of human activities, normalised impact results for a number of impact categories, in particular the toxicity-related impacts, tend to be overestimated [36,72]. Therefore, LCA practitioners should: (i) take into account such methodological uncertainties associated with normalisation references, and the existence of possible biases in their results when they use the normalisation step; (ii) make sure that the choice of the normalisation reference reflects the specific goal and scope of their study (e.g. geographical scope of the system should be captured within the scope of the reference situation); and, (iii) carefully relate the obtained normalised results to the analysed system and its context [36].

3.3.2. Hotspots of primary energy demand at the module level

We did not identify a sufficient number of studies having performed hotspot analyses per impact category to make a consistent analysis. However, a number of 15 studies (covering 18 analysed scenarios) conducted hotspot analyses based on primary energy demand to identify where the largest energy demand originated within the production of thin-film modules – see Table 4. Primary energy demand was observed to be mainly affected by electricity-demanding processes rather than materials with high-embedded energy. Across technologies, these are mainly metal deposition processes with vacuum conditions and high temperatures such as ITO sputtering and layer deposition. Only a few studies were found to identify materials with embedded energy as hotspots with the highest contribution to energy demand. These include Al as

M.D. Chatzisideris, N. Espinosa, A. Laurent, F.C. Krebs, Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies, *Sol. Energy Mater. Sol. Cells.* 156 (2016) 2–10. doi:10.1016/j.solmat.2016.05.048.

encapsulation or framing material. In metal-free or ITO-free technologies, main contributors to energy demand are plastics: PET as substrate and encapsulation barriers.

Table 4

Top contributor of primary energy demand at module level classifying between either electricity-intensive processes or energy embedded in materials (15 studies).

LCA study	Technology [scenario]	Top contributor of primary energy demand		Module component
		Electricity-intensive process	Embedded energy in material	
[44]	CdTe		Al	Frame
[51]	CdTe, Zn ₃ P ₂	Substrate cleaning in heated ultrasonic bath cleaning and drying with N ₂		Substrate
	CIGS	Co-evaporation of Cu, In, Ga and selenisation		Active layer
	CZTS	Co-sputtering of Cu, Zn, Sn and sulphurisation		Active layer
[46]	a-Si/nc-Si	PECVD ^a		Active layer
[48]	a-Si/nc-Si	PECVD ^a		Active layer
[53]	PSC [TiO ₂]		Au	Back electrode
	PSC [ZnO]	ITO sputtering		Transparent electrode
[55]	OPV	N ₂ glove box		Active layer, back electrode, encapsulation
[56]	OPV	ITO sputtering		Transparent electrode
[57]	OPV	Al/Cr sputtering		Back electrode
[58]	OPV [ITO-free]		PET film	Substrate and encapsulation barriers
[59]	OPV	PEDOT:PSS slot-die coating and drying		Hole-transport layer
[60]	OPV	ITO sputtering		Transparent electrode
[61]	OPV [ITO-free]		PET film	Substrate and encapsulation barriers
[66]	QDPV		Al, ETFE ^b , EVA ^c	Encapsulation
[67]	GaAs	MOVPE ^d		Cell stack
[68]	GaAs	MOVPE ^d		Cell stack

^a Plasma-enhanced chemical vapour deposition

^b Ethylene tetrafluoroethylene

^c Ethyl vinyl acetate

^d Metal-organic vapour phase epitaxy

3.3.3. Contribution of BOS components to environmental impacts

A number of 10 studies from Set 2 investigated the contribution of BOS components to the environmental burden [31,40,45,47–50,54,62,66] – see Table S.10. BOS components comprise a large variety of components, such as electrical equipment, e.g. inverters and cabling, support structures or mounting materials. Across technologies, contribution of BOS to environmental impacts was found to be significant, ranging from 3% to 95% depending on the impact category. With respect to climate change, ranges between 31-45% can be observed taking as examples the two studies with cradle-to-grave system boundaries [31,40]. These findings demonstrate the significant influence of BOS components on the environmental performance across impact categories and especially on climate change. The detailed analysis of BOS components in LCA studies can be expected to be even more relevant in the future. In pursuit of NZEB targets and cost savings, BIPV applications will thus involve replacement of building envelope materials, including customisation and aesthetic improvements [5]. In such contexts, it is important that the thin-film PV system is assessed together with its building framework.

Technology developers are therefore recommended to extend their ecodesign focus beyond the sole consideration of the thin-film PV modules, and include the BOS components as well. Not doing so may still induce continuous environmental improvements of the thin-film PV modules, but may also lead the environmental performances of the entire system reach a plateau (as the contribution of BOS components remains unchanged) or increase if impacts of the BOS components increase as a result of newly developed thin-film PV technologies.

4. Conclusions and recommendations

This work extends the scope of available literature that has mostly focused on GHG emissions and energy-related indicators to document environmental performance of thin-film PV systems. A total number of 31 LCA studies of thin-film PV technologies were reviewed to investigate opportunities for technological improvements and mitigation of environmental impacts. Only five studies were found to consider the complete PV life cycle, and present results for more than one environmental problem. Analyses of these studies highlighted the risk of shifting environmental burden from one life cycle stage to another or from one environmental problem to another as well as missed opportunities to improve the environmental performance, when LCA studies (i) omit the disposal stage, or (ii) limit their scope of environmental impact assessment to climate change. Based on our findings, we address LCA practitioners and PV technology developers to stress the importance of considering (i) the entire PV life cycle, including the often omitted disposal stage, and (ii) potential impacts to all environmental problems not only climate change or energy-related indicators, so that possible trade-offs can be identified and assessed.

A number of 28 LCA studies were brought into focus for having utilised LCA as an ecodesign tool. Their analysis demonstrates how thin-film PV stakeholders can benefit from LCA to guide scientific research and technological development. Although great caution should be exercised when interpreting normalised LCA results, findings among 10 studies indicate that PV technology developers should carefully consider toxicity-related and resource depletion impacts. Hotspot analyses of the primary energy demand at module level in 15 studies pointed out to large impacts stemming from electricity consumption during metal deposition processes with requirements for vacuum environment and high temperatures; stakeholders in thin-film PV should therefore closely monitor these processes. Despite the fact that only one third of the reviewed studies

have included them in their assessments, the BOS components were found to have a large contribution to the total environmental burden of the PV systems for many environmental impacts. We therefore strongly recommend LCA practitioners and PV technology developers to systematically include the BOS components in their assessments to optimise the environmental performances of the PV systems, and avoid any burden-shifting from the PV modules to the BOS.

Future research work can widen the focus beyond research scientists and technology developers. Initiatives to develop formal environmental (as well as health and safety) performance ratings for the photovoltaic industry [73] indicate how information about the environmental performance of PV systems is becoming more valuable to a wider circle of stakeholders including end users, PV installers and financial investors. Since their choices could potentially have significant influence on the PV market, future work can consider how these stakeholders could be better informed from a holistic perspective based on LCA findings.

Acknowledgements

We would like to acknowledge financial support from the Climate Knowledge and Innovation Community platform of the European Institute of Innovation and Technology (Project ID: APED0144_2015-1.1-206_P240-26).

References

- [1] Energy Technology Perspectives 2010: Scenarios and Strategies 2050, OECD Publishing, 2009. doi:10.1787/energy_tech-2010-en.
- [2] Solar Photovoltaic Energy, OECD Publishing, 2015. doi:10.1787/9789264238817-en.
- [3] S. Wittkopf, S. Valliappan, L. Liu, K.S. Ang, S.C.J. Cheng, Analytical performance monitoring of a 142.5kWp grid-connected rooftop BIPV system in Singapore, *Renew. Energy.* 47 (2012) 9–20. doi:10.1016/j.renene.2012.03.034.
- [4] P.A. Fokaides, Towards Zero Energy Buildings (ZEB), in: *Green Ecol. Technol. Urban Plan.*, IGI Global, : pp. 93–111. doi:10.4018/978-1-61350-453-6.ch006.
- [5] A. Kylili, P.A. Fokaides, Investigation of building integrated photovoltaics potential in achieving the zero energy building target, *Indoor Built Environ.* 23 (2014) 92–106. doi:10.1177/1420326X13509392.
- [6] J. Jean, P.R. Brown, R.L. Jaffe, T. Buonassisi, V. Bulović, Pathways for solar photovoltaics, *Energy Environ. Sci.* 8 (2015) 1200–1219. doi:10.1039/C4EE04073B.
- [7] E.G. Hertwich, T. Gibon, E.A. Bouman, A. Arvesen, S. Suh, G.A. Heath, et al., Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies., *Proc. Natl. Acad. Sci. U. S. A.* 112 (2014) 6277–6282. doi:10.1073/pnas.1312753111.
- [8] A. Laurent, N. Espinosa, Environmental impacts of electricity generation at global, regional and national scales in 1980–2011: what can we learn for future energy planning?, *Energy Environ. Sci.* 8

- (2015) 689–701. doi:10.1039/C4EE03832K.
- [9] K. Zweibel, The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, *Science* (80-.). 328 (2010) 699–701. doi:10.1126/science.1189690.
- [10] N.G. Dhere, Scale-up issues of CIGS thin film PV modules, *Sol. Energy Mater. Sol. Cells*. 95 (2011) 277–280. doi:10.1016/j.solmat.2010.02.019.
- [11] C. Candelise, M. Winkler, R. Gross, Implications for CdTe and CIGS technologies production costs of indium and tellurium scarcity, *Prog. Photovoltaics Res. Appl.* 20 (2012) 816–831. doi:10.1002/pip.2216.
- [12] ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework.
- [13] ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines.
- [14] V. Fthenakis, R. Frischknecht, M. Rauegi, H.C. Kim, E. Alsema, M. Held, et al., *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, IEA PVPS Task 12, International Energy Agency Photovoltaic Power Systems Programme, 2011.
- [15] D. Weisser, A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies, *Energy*. 32 (2007) 1543–1559. doi:10.1016/j.energy.2007.01.008.
- [16] Varun, I.K. Bhat, R. Prakash, LCA of renewable energy for electricity generation systems—A review, *Renew. Sustain. Energy Rev.* 13 (2009) 1067–1073. doi:10.1016/j.rser.2008.08.004.
- [17] A.F. Sherwani, J.A. Usmani, Life cycle assessment of solar PV based electricity generation systems: A review, *Renew. Sustain. Energy Rev.* 14 (2010) 540–544. doi:10.1016/j.rser.2009.08.003.
- [18] H.C. Kim, V. Fthenakis, J.-K. Choi, D.E. Turney, Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation, *J. Ind. Ecol.* 16 (2012) S110–S121. doi:10.1111/j.1530-9290.2011.00423.x.
- [19] H.C. Kim, V. Fthenakis, Life Cycle Energy and Climate Change Implications of Nanotechnologies, *J. Ind. Ecol.* 17 (2013) 528–541. doi:10.1111/j.1530-9290.2012.00538.x.
- [20] S. Lizin, S. Van Passel, E. De Schepper, W. Maes, L. Lutsen, J. Manca, et al., Life cycle analyses of organic photovoltaics: a review, *Energy Environ. Sci.* 6 (2013) 3136. doi:10.1039/c3ee42653j.
- [21] N.Y. Mansouri, R.J. Crookes, T. Korakianitis, A projection of energy consumption and carbon dioxide emissions in the electricity sector for Saudi Arabia: The case for carbon capture and storage and solar photovoltaics, *Energy Policy*. 63 (2013) 681–695. doi:10.1016/j.enpol.2013.06.087.
- [22] N.Y. Amponsah, M. Troldborg, B. Kington, I. Aalders, R.L. Hough, Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations, *Renew. Sustain. Energy Rev.* 39 (2014) 461–475. doi:10.1016/j.rser.2014.07.087.
- [23] D. Nugent, B.K. Sovacool, Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey, *Energy Policy*. 65 (2014) 229–244. doi:10.1016/j.enpol.2013.10.048.
- [24] R. Turconi, A. Boldrin, T. Astrup, Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations, *Renew. Sustain. Energy Rev.* 28 (2013) 555–565. doi:10.1016/j.rser.2013.08.013.

- [25] B. Bakhiyi, F. Labrèche, J. Zayed, The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues, *Environ. Int.* 73 (2014) 224–234. doi:10.1016/j.envint.2014.07.023.
- [26] F. Asdrubali, G. Baldinelli, F. D’Alessandro, F. Scrucca, Life cycle assessment of electricity production from renewable energies: Review and results harmonization, *Renew. Sustain. Energy Rev.* 42 (2015) 1113–1122. doi:10.1016/j.rser.2014.10.082.
- [27] C. Lamnatou, D. Chemisana, R. Mateus, M.G. Almeida, S.M. Silva, Review and perspectives on Life Cycle Analysis of solar technologies with emphasis on building-integrated solar thermal systems, *Renew. Energy*. 75 (2015) 833–846. doi:10.1016/j.renene.2014.09.057.
- [28] J. Peng, L. Lu, H. Yang, Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems, *Renew. Sustain. Energy Rev.* 19 (2013) 255–274. doi:10.1016/j.rser.2012.11.035.
- [29] S. Gerbinet, S. Belboom, A. Léonard, Life Cycle Analysis (LCA) of photovoltaic panels: A review, *Renew. Sustain. Energy Rev.* 38 (2014) 747–753. doi:10.1016/j.rser.2014.07.043.
- [30] A. Laurent, S.I. Olsen, M.Z. Hauschild, Limitations of Carbon Footprint as Indicator of Environmental Sustainability, *Environ. Sci. Technol.* 46 (2012) 4100–4108. doi:10.1021/es204163f.
- [31] N. Espinosa, A. Laurent, F.C. Krebs, Ecodesign of organic photovoltaic modules from Danish and Chinese perspectives, *Energy Environ. Sci.* 8 (2015) 2537–2550. doi:10.1039/C5EE01763G.
- [32] C. Dalhammar, E. Machacek, A. Bundgaard, K.O. Zacho, A. Remmen, Addressing resource efficiency through the Ecodesign Directive, Copenhagen, 2014. doi:10.6027/TN2014-511.
- [33] M.P. Tsang, G.W. Sonnemann, D.M. Bassani, A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells, *Prog. Photovoltaics Res. Appl.* 24 (2016) 645–655. doi:10.1002/pip.2704.
- [34] IEC 62430:2009 Environmentally conscious design for electrical and electronic products.
- [35] M.A.J. Huijbregts, L.J.A. Rombouts, S. Hellweg, R. Frischknecht, A.J. Hendriks, D. van de Meent, et al., Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?, *Environ. Sci. Technol.* 40 (2006) 641–648. doi:10.1021/es051689g.
- [36] Laurent A., Hauschild M.Z. 2015. Normalisation in LCA (Chapter 14, pp. 271-300). In: *LCA Compendium - The Complete World of Life Cycle Assessment* (Series Eds. Klöpffer W, Curran MA), *Life Cycle Impact Assessment* (Eds. Hauschild M.Z., Huijbregts M.A.J.). Springer, Dordrecht, NL. doi:10.1007/978-94-017-9744-3_14
- [37] Eco-indicator. <https://www.pre-sustainability.com/> (accessed October 28, 2015).
- [38] CML. <http://cml.leiden.edu/software/data-cmlia.html> (accessed October 28, 2015).
- [39] ReCiPe. <http://www.lcia-recipe.net/> (accessed November 2, 2015).
- [40] M. Held, R. Ilg, Update of environmental indicators and energy payback time of CdTe PV systems in Europe, *Prog. Photovoltaics Res. Appl.* 19 (2011) 614–626. doi:10.1002/pip.1068.
- [41] E. Carnevale, L. Lombardi, L. Zanchi, Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at domestic scale, *Energy*. 77 (2014) 434–446.

doi:10.1016/j.energy.2014.09.028.

- [42] L. Serrano-Luján, R. García-Valverde, N. Espinosa, M.S. García-Cascales, J.M. Sánchez-Lozano, A. Urbina, Environmental benefits of parking-integrated photovoltaics: a 222 kWp experience, *Prog. Photovoltaics Res. Appl.* 23 (2015) 253–264. doi:10.1002/pip.2415.
- [43] P.K. Ng, N. Mithraratne, Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics, *Renew. Sustain. Energy Rev.* 31 (2014) 736–745. doi:10.1016/j.rser.2013.12.044.
- [44] K. Kato, T. Hibino, K. Komoto, S. Ihara, S. Yamamoto, H. Fujihara, A life-cycle analysis on thin-film CdS/CdTe PV modules, *Sol. Energy Mater. Sol. Cells*. 67 (2001) 279–287. doi:10.1016/S0927-0248(00)00293-2.
- [45] M. Raugei, S. Bargigli, S. Ulgiati, Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si, *Energy*. 32 (2007) 1310–1318. doi:10.1016/j.energy.2006.10.003.
- [46] H.C. Kim, V.M. Fthenakis, Comparative life-cycle energy payback analysis of multi-junction a-SiGe and nanocrystalline/a-Si modules, *Prog. Photovoltaics Res. Appl.* 19 (2011) 228–239. doi:10.1002/pip.990.
- [47] R. van der Meulen, E. Alsema, Life-cycle greenhouse gas effects of introducing nano-crystalline materials in thin-film silicon solar cells, *Prog. Photovoltaics Res. Appl.* 19 (2011) 453–463. doi:10.1002/pip.1058.
- [48] N.J. Mohr, A. Meijer, M.A.J. Huijbregts, L. Reijnders, Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate, *Prog. Photovoltaics Res. Appl.* 21 (2013) n/a–n/a. doi:10.1002/pip.2157.
- [49] H. Kim, K. Cha, V.M. Fthenakis, P. Sinha, T. Hur, Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems, *Sol. Energy*. 103 (2014) 78–88. doi:10.1016/j.solener.2014.02.008.
- [50] J.D. Bergesen, G.A. Heath, T. Gibon, S. Suh, Thin-Film Photovoltaic Power Generation Offers Decreasing Greenhouse Gas Emissions and Increasing Environmental Co-benefits in the Long Term, *Environ. Sci. Technol.* 48 (2014) 9834–9843. doi:10.1021/es405539z.
- [51] J. Collier, S. Wu, D. Apul, Life cycle environmental impacts from CZTS (copper zinc tin sulfide) and Zn₃P₂ (zinc phosphide) thin film PV (photovoltaic) cells, *Energy*. 74 (2014) 314–321. doi:10.1016/j.energy.2014.06.076.
- [52] N. Espinosa, L. Serrano-Luján, A. Urbina, F.C. Krebs, Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective, *Sol. Energy Mater. Sol. Cells*. 137 (2015) 303–310. doi:10.1016/j.solmat.2015.02.013.
- [53] J. Gong, S.B. Darling, F. You, Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts, *Energy Environ. Sci.* 8 (2015) 1953–1968. doi:10.1039/C5EE00615E.
- [54] A.L. Roes, E.A. Alsema, K. Blok, M.K. Patel, Ex-ante environmental and economic evaluation of polymer photovoltaics, *Prog. Photovoltaics Res. Appl.* 17 (2009) 372–393. doi:10.1002/pip.891.
- [55] R. García-Valverde, J.A. Cherni, A. Urbina, Life cycle analysis of organic photovoltaic technologies, *Prog. Photovoltaics Res. Appl.* 18 (2010) 535–558. doi:10.1002/pip.967.

- [56] N. Espinosa, R. García-Valverde, A. Urbina, F.C. Krebs, A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions, *Sol. Energy Mater. Sol. Cells.* 95 (2011) 1293–1302. doi:10.1016/j.solmat.2010.08.020.
- [57] N. Espinosa, R. García-Valverde, A. Urbina, F. Lenzmann, M. Manceau, D. Angmo, et al., Life cycle assessment of ITO-free flexible polymer solar cells prepared by roll-to-roll coating and printing, *Sol. Energy Mater. Sol. Cells.* 97 (2012) 3–13. doi:10.1016/j.solmat.2011.09.048.
- [58] N. Espinosa, M. Hösel, D. Angmo, F.C. Krebs, Solar cells with one-day energy payback for the factories of the future, *Energy Environ. Sci.* 5 (2012) 5117–5132. doi:10.1039/C1EE02728J.
- [59] C.J.M. Emmott, A. Urbina, J. Nelson, Environmental and economic assessment of ITO-free electrodes for organic solar cells, *Sol. Energy Mater. Sol. Cells.* 97 (2012) 14–21. doi:10.1016/j.solmat.2011.09.024.
- [60] A. Anctil, C.W. Babbitt, R.P. Raffaele, B.J. Landi, Cumulative energy demand for small molecule and polymer photovoltaics, *Prog. Photovoltaics Res. Appl.* 21 (2013) 1541–1554. doi:10.1002/pip.2226.
- [61] N. Espinosa, F.C. Krebs, Life cycle analysis of organic tandem solar cells: When are they warranted?, *Sol. Energy Mater. Sol. Cells.* 120 (2014) 692–700. doi:10.1016/j.solmat.2013.09.013.
- [62] N. Espinosa, M. Hösel, M. Jørgensen, F.C. Krebs, Large scale deployment of polymer solar cells on land, on sea and in the air, *Energy Environ. Sci.* 7 (2014) 855. doi:10.1039/c3ee43212b.
- [63] R.R. Søndergaard, N. Espinosa, M. Jørgensen, F.C. Krebs, Efficient decommissioning and recycling of polymer solar cells: justification for use of silver, *Energy Environ. Sci.* 7 (2014) 1006. doi:10.1039/c3ee43746a.
- [64] H. Greijer, L. Karlson, S.-E. Lindquist, Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system, *Renew. Energy.* 23 (2001) 27–39. doi:10.1016/S0960-1481(00)00111-7.
- [65] M.L. Parisi, S. Maranghi, R. Basosi, The evolution of the dye sensitized solar cells from Grätzel prototype to up-scaled solar applications: A life cycle assessment approach, *Renew. Sustain. Energy Rev.* 39 (2014) 124–138. doi:10.1016/j.rser.2014.07.079.
- [66] H. Şengül, T.L. Theis, An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use, *J. Clean. Prod.* 19 (2011) 21–31. doi:10.1016/j.jclepro.2010.08.010.
- [67] A. Meijer, M.A.J. Huijbregts, J.J. Schermer, L. Reijnders, Life-cycle assessment of photovoltaic modules: Comparison of mc-Si, InGaP and InGaP/mc-Si solar modules, *Prog. Photovoltaics Res. Appl.* 11 (2003) 275–287. doi:10.1002/pip.489.
- [68] N.J. Mohr, J.J. Schermer, M.A.J. Huijbregts, A. Meijer, L. Reijnders, Life cycle assessment of thin-film GaAs and GaInP/GaAs solar modules, *Prog. Photovoltaics Res. Appl.* 15 (2007) 163–179. doi:10.1002/pip.735.
- [69] N. Mohr, A. Meijer, M.A.J. Huijbregts, L. Reijnders, Environmental impact of thin-film GaInP/GaAs and multicrystalline silicon solar modules produced with solar electricity, *Int. J. Life Cycle Assess.* 14 (2009) 225–235. doi:10.1007/s11367-009-0062-z.
- [70] M. Münster, G. Finnveden, H. Wenzel, Future waste treatment and energy systems – examples of

joint scenarios, *Waste Manag.* 33 (2013) 2457–2464. doi:10.1016/j.wasman.2013.07.013.

- [71] T.F. Astrup, D. Tonini, R. Turconi, A. Boldrin, Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations, *Waste Manag.* 37 (2015) 104–115. doi:10.1016/j.wasman.2014.06.011.
- [72] A. Laurent, A. Lautier, R.K. Rosenbaum, S.I. Olsen, M.Z. Hauschild, Normalization references for Europe and North America for application with USEtox™ characterization factors, *Int. J. Life Cycle Assess.* 16 (2011) 728–738. doi:10.1007/s11367-011-0285-7.
- [73] D. Mulvaney, Solar's green dilemma, *IEEE Spectr.* 51 (2014) 30–33. doi:10.1109/MSPEC.2014.6882984.