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A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory

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ABSTRACT

Life Cycle Assessments (LCA) of single-crystalline silicon (sc-Si) photovoltaic (PV) systems often disregard novel module designs (e.g. glass-glass modules) and the fast pace of improvements in production. This study closes this research gap by comparing the environmental impacts of sc-Si glass-backsheet and glass-glass modules produced in China, Germany and the European Union (EU), using current inventory data. Results show lower potential environmental impacts for glass-glass compared to glass-backsheet modules and lower impacts for production in the EU and Germany compared to China for most impact categories. Concerning climate change, glass-backsheet (glass-glass) modules produced in China, Germany or the EU are linked to emissions of 810 (750), 580 (520) and 480 (420) kg CO_2-eq/kW_p, respectively. This corresponds to CO_2-eq emission reductions of 30% for German and 40% for European production compared to Chinese production, and 8–12.5% reduction in glass-glass compared to glass-backsheet modules. Carbon intensity of produced electricity, excluding balance of system (BOS), amounts to 13–30 g CO_2-eq/kWh, depending on production location and electricity yield calculation method. A warranty-based yield calculation method shows the influence of different lifetime electricity yields of glass-glass and glass-backsheet modules on the potential environmental impacts. This study identifies module efficiency, energy requirements, silicon consumption and carbon-intensity of electricity during production as significant levers for future reductions of environmental impacts. It emphasizes the importance of up-to-date inventories and current modelling of electricity mixes for representative LCA results of PV modules. Lastly, this paper argues that more differentiated methodological guidelines are needed to incentivize the development of sustainable module designs.

1. Introduction

To limit global warming below the 2 °C threshold of the Paris agreement, a rapid decarbonisation of the global energy supply by shifting from fossil-based to renewable energies, such as photovoltaic (PV), is needed [1]. Despite PV's "emission-free conversion" of sunlight into electricity [2], PV electricity still causes environmental impacts during the extraction of raw materials, their processing and assembly into PV systems [3]. These embedded impacts need to be accurately quantified to understand the overall environmental profile of PV technologies and to allow for a meaningful comparison with other energy sources [4]. Life cycle assessment (LCA) is a well-established method to evaluate potential environmental impacts caused by a product or a process throughout its entire life cycle [5]. LCA is governed by ISO standards 14040–44 [6,7] and is supported by general guidelines by the EU [8–12] as well as PV-specific guidelines [13,14]. The abundant body of PV LCAs can be studied in various literature reviews [15–20]. A tabular summary of recent LCAs on single-crystalline silicon (sc-Si) PV systems is given in Table 2. This overview shows highly diverging results of existing PV LCAs - even for the same PV technology -, which can be explained by differences in inventory data (e.g. electricity mixes, material consumption and energy requirements), differences in system boundaries (e.g. inclusion or exclusion of balance of system (BOS), transport and end-of-life treatment) and differences in operation parameters (e.g. solar irradiation, lifetime, module efficiency and performance ratio) [15,21].

Existing PV LCAs are often based on outdated life cycle inventory (LCI) data. The two prominently used LCI sources are the Ecoinvent PV datasets [22], which reflect crystalline silicon PV module production in 2005, and the IEA PVPS 2015 datasets [3], which reflect crystalline silicon PV module

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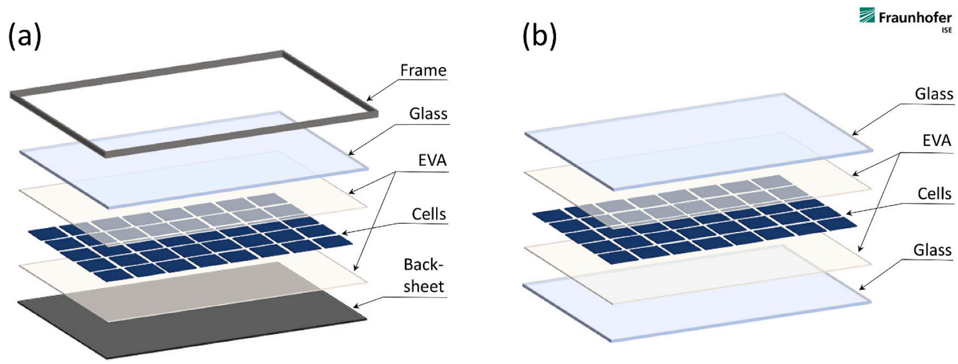

Fig. 1. Structure of glass-backsheet (G-BS) module (a) and glass-glass (G–G) module (b).

production in 2011. Given the rapid reductions in energy and material consumption in the PV industry and the significant increase in module efficiencies since then [23], studies based on these old inventories are likely to overestimate the environmental impact of PV systems. Moreover, the recent shift in production to China is not always accounted for in PV LCAs [24], and despite scientific efforts to compile LCIs from Chinese producers [3,25–28], the historic focus on inventory data from European producers prevails [28]. In late 2020, IEA PVPS released an updated LCI for PV systems that contains updates for crystalline silicon PV technology reflecting the year 2018, while some information, such as the amounts of auxiliary materials, are still based on 2011 [29]. Due to the recentness of this publication, it has not yet been widely applied in the scientific community. As described in section 1.2, this study uses a current LCI based on industry data [30] and compares it to other commonly used LCIs [3,22] in the sensitivity analysis.

The existing literature also gives little attention to new developments in module designs of crystalline silicon PV systems. Alternatives to the conventional glass-backsheet (G-BS) layout, such as glass-glass (G-G) design, are rarely studied. The G-G design has emerged as a promising alternative, with 10% market share in 2019 and expected 30% market share by 2030 [23]. Its lower water vapor ingress and reduced mechanical cell stress under load allow for lower degradation rates (DR) and longer lifetimes compared to conventional G-BS modules [31,32]. Although the double-glass layout offers sufficient mechanical stability on its own [31] and the omission of the frame leads to cost reductions, not all G-G modules are produced without a frame [33]. However, in order to contrast the differences between G-G and G-BS module designs, this study focuses on frameless G-G modules, excluding framed G-G modules. Despite their potential, there is a lack of LCAs on glass-glass modules with only one peer-reviewed study assessing this module design and only for multi-crystalline silicon cells [34]. Not only scientific studies but also regulatory literature fails to acknowledge different module designs. By recommending the same degradation rates and lifetimes for all module designs despite proven diverging performances in the field [35,36], the guideline for LCA of PV systems by the IEA PVPS [13] fails to encourage a differentiated comparison of different module designs. However, this guideline permits to use long-term, site-specific data to allow for a differentiation between real-life installations [13]. Yet, long-term installation data is often not available to LCA practitioners.

This study will be useful for future PV LCA practitioners as it comprehensively addresses the potential environmental impact of single-crystalline silicon glass-glass modules compared to glass-backsheet modules, produced in China, Germany and the European Union (EU), using state-of-the-art inventory. It is also helpful for policy makers as it highlights the need for differentiated LCA guidelines for different PV systems and emphasizes the importance of updated inventories.

2. Methodology

2.1. LCA goal & scope

The primary objective of this study is to assess the differences in potential environmental impact between single-crystalline silicon glass-backsheet (G-BS) and glass-glass (G-G) PV systems using the current state of technology for production locations in China, Germany and the EU. Results are given per kW_p nameplate power as well as per kWh of produced electricity. In addition to the recommended calculation methods by the International Energy Agency (IEA) LCA guidelines for PV systems [13], a

Table 1
Technical details of modules under review.

Parameter	Unit	Glass-backsheet module	Glass-glass module	Source
Module				
Reference flow	m^2/kW_p	5.052	5.156	Own calc.
Rated Power	W_p	366	359	Own calc.
Module size	m^2	1.85	1.85	Own calc.
Number of cells	pcs.	60	60	[23]
CTM	%	99	97	[39]
Module efficiency	%	19.79	19.40	Own calc.
Glass thickness	mm	3.2	2x 2.0	[23]
Backsheet	µm	25 PVT, 250 PET, 60 Polyolefin	no	[30]
Aluminum frame	kg	2.80	no	[30]
Cell				
Cell type		full-cell M6 psq sc-Si Cz PERC p-type[a]		[30]
Cell efficiency	%	22.5		[23]
Cell area	cm^2	274.15		[30]
Wafer thickness	µm	170		[30]
Kerfloss	µm	80		[30]
Poly-Si consumption	g/wafer	18.0		[30]

[a] This study uses full-cell format whereas Friedrich et al., t.b.p [30]. uses half-cell format.

Table 2
Tabular overview of LCAs of PV systems with focus on single-crystalline silicon (sc-Si) technologies, PERC cells or glass-glass module design. Publications are listed chronologically, and key parameters are compared. Results are only listed for sc-Si PV technologies if multiple PV technologies were assessed. Unless specified otherwise, all results refer to glass-backsheet module designs.

Authors & Reference	Year	Location	Methodological choices			Technical parameters				Results		Remarks
			Technology reviewed	LCI source	System boundaries	Module eff. [%]	Irradiation [kWh/ (m^2*yr)]	LT [yr]	PR	GWP of rated power [kg CO_2/ kW_p]	GWP of electricity [g CO_2/kWh]	
Alsema & Wild-Scholten [41]	2005	Europe	sc-, mc-, ribbon Si	European & US PV company data	Cradle-to-gate, including BOS	14	1700	30	0.75	N/A	45 Future: 13	First comprehensive LCI based on 2004 data
Wild-Scholten [42]	2013	Europe, China	sc- and various other PV technologies	(partly unpubl.) industry and company data	Cradle-to-gate, including BOS	14.8	1700	30	0.75	1220 (EU, only panel), 1408[a] (EU, PV sys.), 2810 (CN, only panel), 2998[a] (CN, PV sys.)	33 (EU, only panel), 38.1 (EU, PV sys.) 76.1 (CN only panel), 81.2 (CN, PV sys.)	[a] typo in original document Production in Europe is assumed with hydro/UTCE electricity, production in China with average Chinese electricity mix
Yue et al. [43]	2014	Europe, China	sc-, mc-Si and ribbon Si	Ecoinvent v2.2, CLCD v0.8	Cradle-to-grave, excluding BOS and transport from CN to EU	14	1700	30	0.75	1430 (EU), 2760 (CN)	37.3 (EU), 72.2 (CN)	Cradle-to-grave approach, but not mentioning source for EoL-LCI. Excluding BOS and transport to Europe
Kim et al. [44]	2014	Korea	sc- and mc-Si	Literature, company data	Cradle-to-grave, including BOS	15.96	1310	30	0.80	N/A	41.9 (incl. BOS)	LCIs gained from company data not fully disclosed
Louwen et al. [45]	2015	Europe	sc- and SHJ-Si	Ecoinvent v2.1, literature, equipment data	Raw material to operation, including BOS, excluding EoL	16.1, 19.5 (2020 scenario)	1700	30	0.75	N/A	38 (incl BOS, 2015), 25 (incl. BOS, 2020 scenario)	sc-Si modules are only reference case for study on SHJ modules. 2020 scenario: wafer thickness assumed only 50 µm.
Leccisi et al. [46]	2016	Europe, US, China	sc-, mc-Si, CdTe, CIGS	IEA PVPS 2015	Panel and BOS, excluding EoL	17	1000–2300	30	0.80	1200 (sc-Si, excl. BOS, Europe), 1700 (sc-Si, excl. BOS, China)	28 (Europe, 2300 kWh/m^2yr irrad.) to 83 (China, 1000 kWh/m^2yr irrad.)	Production not entirely in one country: Europe: 89% European wafers and 11% Chinese wafers. No update for material improvements
Chen et al. [27]	2016	China	sc-Si	Chin. cell producer data, Ecoinvent v3.1	Cradle-to-gate, excluding BOS and EoL	15.7	1139–2453	25	–	285	5.6 (excl. BOS, 2453 kWh/m^2yr irrad.) to 12.1 (excl. BOS, 1139 kWh/m^2yr)	Extremely low values. PR not disclosed (likely 1). BOS and EoL excluded. Inputs to poly-Si, Cz-crystal and wafering not disclosed.
Hong et al. [28]	2016	China	mc-Si	Chin. cell producer data, Ecoinvent v2.2	Cradle-to-gate, excluding BOS and EoL	12.7	1300	25	–	1840 (mc-Si, excl. BOS China)	No sc-Si covered 56.15 (mc-Si, excl. BOS, China)	PR not disclosed (likely 1). BOS and EoL excluded. Confusing use of the term “cell”, potentially referring to PV modules
Stamford et al. [47]	2018	Germany or China. Install. in Spain or UK	sc- and mc-Si	IEA PVPS 2015, technology roadmaps	Cradle-to-grave, including BOS, excluding EoL	16.4	873 kWh/kW_p (UK) 1500 kWh/kW_p (Spain)	30	–	N/A	49 (DE-UK), 59.4 (CN-UK), 28.5 (DE-Spain), 34.6 (CN-Spain)	PR not disclosed separately but included in yield.
Wambach et al. [48]	2018	Europe	sc- and mc-Si	IEA PVPS 2015, project partners	Cradle-to-grave, including BOS and EoL	–	–	–	–	1333 (sc-Si), 830 (mc-Si)	–	No disclosure of module efficiency and wafer thickness, same module power of 270 Wp for sc-Si and mc-Si modules
Luo et al. [34]	2018	Singapore	mc-Si: Al-BSF vs. PERC, G-G and G-BS module design	Ecoinvent v3.3, IEA PVPS 2015, research	Cradle-to-grave, including BOS, excluding transport, EoL	16.7 (mc-Si, G-BS), 16.2 (mc-Si, G-G)	1580	25 (G-BS), 30 (GG)	0.785	821[b] (mc-Si, PERC, G-BS), 767[b] (mc-Si, PERC, G-G)	No sc-Si covered, 29.2 (mc-Si, PERC, G-BS, incl. BOS),	[b] assuming 1.6m^2 module area, module area and power rating not disclosed. Very favorable system

(*continued on next page*)

Table 2 (*continued*)

Authors & Reference	Year	Location	Methodological choices: Technology reviewed	LCI source	System boundaries	Technical parameters: Module eff. [%]	Irradiation [kWh/(m^2*yr)]	LT [yr]	PR	Results: GWP of rated power [kg CO_2/kW_p]	GWP of electricity [g CO_2/kWh]	Remarks
				institute data, literature							20.9 (mc-Si, PERC, G-G, incl. BOS)	performance for glass-glass modules
Lunardi et al. [49]	2018	China	sc-Si: Al-BSF and PERC cells from different feedstocks	Ecoinvent, IEA PVPS 2015, literature	Cradle-to-grave, excluding BOS, use and EoL	18.2 (PERC, poly-Si), 17.1 (Al-BSF, poly-Si)	1700	25	0.75	N/A	19.5 (PERC, poly-Si), 21 (Al-BSF, poly-Si)	Wafer thickness not mentioned explicitly. Ecoinvent version not disclosed
Friedrich et al., t.b.p [30].	2021	China, EU, Norway, Install: EU	sc-Si, PERC half cells	Industry data, Ecoinvent v3.6	Raw material to operation, including BOS, excluding EoL	20.1	1331	30	0.73	480 (NO) 680 (EU) 1270 (CN)	16.5 (NO), 23.2 (EU), 45.3 (CN), all incl. BOS	PR not disclosed in paper but received via personal communication. Lifetime degradation is included in PR.
This study	2021	China, EU, Germany. Install: EU	sc-Si, PERC full cells	Industry data, Ecoinvent v3.7	Cradle-to-grave, excluding BOS and maintenance	19.8 (G-BS), 19.4 (G-G)	1391	30 vs. 25.4 (G-BS) 29.9 (G-G)	0.75 vs 0.85	810 (G-BS, CN), 580 (G-BS, DE), 480 (G-BS, EU), 750 (G-G, CN), 520 (G-G, DE), 420 (G-G, EU), all excl. BOS	12.9 (G-G, EU, LT 29.9 yr, own yield calc.) to 29.9 (G-BS, CN, LT 25.4 yr, own yield calc), all excl. BOS	Two calculation methods were used for impact per kWh: IEA recommendations and average of module power warranties

technology-specific lifetime electricity yield calculation based on average performance warranties by module producers is used for the carbon footprint per kWh of produced electricity, see Table 3. This two-folded approach emphasizes the need for more differentiated assessment guidelines for different PV module technologies.

The secondary objective is to trace the improvements in environmental impacts within the last 10 years by comparing this study to the commonly used life cycle inventories in the field: Ecoinvent v3.7 [22] and IEA PVPS 2015 [3]. This attributional LCA follows ISO 14040–44 [6, 7] and PV LCA guideline by the IEA [13]. It uses the software SimaPro Analyst v9.0 [37]. PV foreground processes are based on Friedrich et al. t.b.p. [30], while background processes are based on Ecoinvent v3.7 [22].

2.1.1. PV system description

This study analyses two monofacial, single-crystalline silicon module designs: framed glass-backsheet (G-BS) and frameless glass-glass (G-G) design (layout given in Fig. 1), produced in China, Germany or the EU. Monofaciality is chosen for both designs to allow for a fair comparison, e.g. no additional rear-side electricity gain for G-G modules through bifaciality. Single-crystalline silicon was chosen over multi-crystalline silicon as it is the leading polysilicon feedstock with a market share of 65% in 2019 and expected market share of 80% by 2030 [23]. The production location China has been selected, representing the majority of PV production [38], while the EU and Germany have been selected to investigate the implications for a potential European and Germany production location.

The main difference between the two designs is that G-G modules are frameless and use two thin (2 mm) glass layers as front and rear encapsulants, whereas the G-BS module is framed and uses a thick (3.2 mm) glass as front encapsulant and a polymer backsheet as rear encapsulant. The technical details of the two designs are listed in Table 1. The power rating of G-BS modules is higher than of G-G modules (366 vs. 359 W_p) as the G-BS design has a higher cell-to-module (CTM) ratio because of optical gains by reflection of sunlight at the encapsulant-backsheet interface in the cell gap region, which is missing in the G-G design [34].

The lifetime electricity E_{total} generated by a PV system can be calculated using equation (1):

$$E_{total} = \sum_{y=1}^{T} \left((1 - DR)^{y} \times I \times A \times \eta \times PR_i \right) \tag{1}$$

where T is the lifetime of the PV modules (years), DR is the mean annual degradation rate, I is the global tilted location-specific average annual solar irradiation (kWh/(m^2yr)), A is the surface area of the PV modules (m^2), η is the module efficiency (%) under standard test conditions (STC) and PR_i is the initial performance ratio. If different degradation rates for the first and consecutive years are given, as it is commonly the case for power warranties of PV modules, equation (1) is adjusted to equation (2):

$$E_{total} = \sum_{y=2}^{T} \left((1 - DR_2)^{y-1} \times (1 - DR_1) \times I \times A \times \eta \times PR_i \right) + (1 - DR_1) \times I \times A \times \eta \times PR_i \tag{2}$$

where DR_1 is the degradation rate in year 1 and DR_2 the degradation rate in year 2 to end of lifetime.

As the total environmental impact per kWh of electricity is inversely proportional to the lifetime electricity generation of PV systems, the correct calculation of the lifetime electricity yield is vital. Apart from technological parameters (e.g. cell efficiency, CTM, module efficiency), operational factors (e.g. solar irradiance, lifetime, performance ratio, degradation rate) strongly influence the yield of the PV system over its lifetime [19,21,24,40]. These factors vary significantly in the literature (see Table 2), rendering comparison of results difficult. To facilitate

Table 3
Parameters for the lifetime electricity yield calculation. Approach 1 is based on IEA LCA PV guidelines [13] while approach 2 uses degradation rates as outlined in power warranties of modules from 2015 to 2020 ($n_{glass\text{-}backsheet} = 263$, $n_{glass\text{-}glass} = 175$). Values for approach 2 are given as mean (±standard deviation). Details of the analysis of power warranties are given in the supplementary information (SI).

	Unit	(1.) LCA PV guideline [13]	Source	(2.) Power warranties		Source
		G-BS and G-G		G-BS	G-G	
Lifetime	year	30	[13]	25.44 (±1.42)	29.89 (±1.51)	Own analysis (see SI)
DR (1st year)	%	Included in PR	[13]	−2.67 (±0.54)	−2.55 (±0.46)	Own analysis (see SI)
DR (follow. Years)	%	Included in PR	[13]	−0.64 (±0.10)	−0.45(±0.09)	Own analysis (see SI)
PR		0.75	[13]	0.85	0.85	[51]
Solar irradiation	kWh/(m^2yr)	1391[a]	[13]	1391[a]	1391[a]	[13]
Reference flow	cm^2/kWh	1.614 (G-BS), 1.648 (G-G)	Own calc.[b]	1.895	1.591	Own calc.[b]

[a] [13] recommend country-specific irradiation based on [52]. [52] lists 1391 kWh/(m^2yr) as the population-weighted average for Europe.
[b] Reference flow is calculated by dividing the module size (see Table 1) by the lifetime electricity yield (E_{total}), which is calculated for (1.) as E_{total} = LT * PR * Solar irradiation and for (2.) based on equation (2).

comparison, the LCA guideline for PV systems by the IEA lists recommendations for these parameters (see Table 3, left) [13]. Unfortunately, these guidelines do not differentiate between different module designs for crystalline PV technologies, and, thus, disregard the differences in field performance and lifetime electricity yields of different module designs [35,36].

To highlight the dependence of results on the choice of yield calculation parameters, this study calculates the lifetime electricity yield of the modules following two approaches: (1.) using recommendations of IEA PV LCA guideline [13], (2.) using power warranties from PV companies (average warranties of 438 modules between 2015 and 2020), see Table 3. Power warranties are chosen as a suitable proxy for actual module performance as they indicate the minimum performance of modules, below which consumers can ask for compensation from manufacturers [50].

2.1.2. *Functional unit and system boundary*

The functional unit (FU) of this study is twofold: (1.) 1 kW_p of nominal module power and (2.) 1 kWh of produced electricity (excluding balance of system (BOS)). The reference flow describes the fraction of the PV module that is required to produce the FU and is listed in Tables 1 and 3. The system boundaries are depicted in Fig. 2. The entire upstream production chain of sc-Si PV panels, transport to installation location and end-of-life treatment is included. BOS is excluded because the focus of this study is on the module components. As BOS is required to deliver electricity to the grid, literature values for the environmental impact of BOS need to be added to the results per kWh of this study, see section 2.2. Use phase is excluded because it is similar for both systems and assumed negligible in literature [25,30].

2.1.3. *Environmental impact assessment methods*

The IEA PV LCA guidelines [13] recommend the 16 impact categories used by the EU product environmental footprint category rules (PEFCR) for PV [14]. All 16 impact categories are assessed in this study. However, in view of the role of PV technologies in the transition to low-carbon energy systems, the focus is on the impact category climate change. Using SimaPro v9.0, the impact category climate change is calculated with the single issue method IPCC 2013, while the other 15 impact categories are calculated with the EF 3.0 (adopted method) as recommended by the PEFCR [14,53,54].

2.2. *Life cycle inventory*

This study uses the most up-to-date inventory data by Fraunhofer ISE (Friedrich et al., t.b.p [30]). [30] investigates the current material input for the processes polysilicon to module production based on a detailed cost model of PV production facilities. Due to a lack of industry data on process emissions, they base emissions on Ecoinvent. End-of-life treatment is modelled based on [55], which assumes the recycling of glass, frame and cabling while silicon components and polymers are landfilled or incinerated. [55] only assesses recycling of G-BS modules, not of G-G modules. Yet, as no LCI for recycling of G-G modules is available, this study assumes that the recycling process is similar for G-G modules and changes the material composition of [55] to the composition of glass-glass and glass-backsheet modules in this study, see supplementary information (SI). Background data of this study is based on Ecoinvent v3.7 [22]. Full inventory data is given in the SI.

In order to create a regional life cycle inventory, Chinese, German and European medium voltage electricity mixes, based on Ecoinvent v3.7 [22], are used in all PV manufacturing processes and for selected intermediate products (TMAI, silver paste, aluminium alloy and solar glass production). This approach diverges from IEA PVPS Task 12's approach for regional inventories in their 2015 LCI [3], which models European MG-silicon production with Norwegian electricity and European polysilicon purification with a high share of hydropower but applies the average Chinese electricity mix throughout the entire Chinese

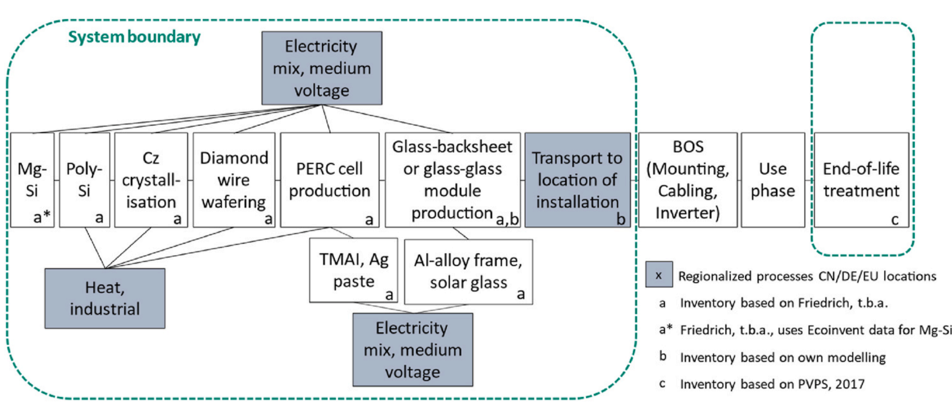

Fig. 2. System boundaries of this study. Adopted from Friedrich et al., t.b.p [30]. Ecoinvent v3.7 [22] is used in this study.

Table 4
Overview of most important parameters and assumptions of the LCIs compared in the sensitivity analysis: Ecoinvent v.3.7 [22], IEA PVPS 2015 [3] and this study for glass-backsheet module production in the EU.

	Unit	Ecoinvent v3.7 [22]	IEA PVPS 2015 [3]	This study [30]
Reference year of LCI		2005	2011	2020[a]
Module power	W_p	224	224	366
Module efficiency	%	14	14	19.8
Wafer thickness	μm	270	270	170
Kerfloss	μm	191	145	80
Wafer sawing method		Slurry based	Slurry based	Diamond wire sawing
Electricity consumption		MG-Si: Norwegian electricity, poly-Si: 60% hydroelectricity, Rest: EU medium voltage grid mix (year 2017)	MG-Si: Norwegian electricity, poly-Si: 60% hydroelectricity, Rest: EU medium voltage grid mix (year 2017)	Only EU medium voltage grid mix (year 2017)
MG-Si	kWh/kg	11	11	11
Poly-Si	kWh/kg	110	110	72
Cz-Si	kWh/kg	85.6	68.2	38.4
Wafering	kWh/m^2	8	25.7	2.35
Cell	kWh/m^2	30.2	14.4	6.24
Module	kWh/m^2	4.71	3.73	3.32
Silicon consumption				
MG-Si	kg Si Sand/kg MG Si	2.7	2.7	2.7
Poly-Si	kg MG Si/kg Poly-Si	1.13	1.13	1.13
Cz-Si	kg Poly-Si/kg Cz Si	1.07	0.781[b]	0.639[b]
Wafering	kg Cz Si/m^2 wafer	1.07	1.58	1.03
Cell	m^2 wafer/m^2 cell	1.06	1.03	1.02
Module	m^2 cell/m^2 module	0.932	0.935	0.898
Poly-Si composition		Mix of electronics grade (14,6%) and solar grade (85,4%) silicon	Mix of electronic grade (14.6%), solar grade (80.2%) and off-grade (5.2%) Si.	Only solar grade silicon
Aluminium	kg/m^2 module	2.63	2.13	1.51
Glass	kg/m^2 module	10.1	8.81	8.00

[a] Reference year for foreground LCI is 2020 [30], while background processes from Ecoinvent have older reference years [22].
[b] Input of recycled Cz-crystal (corners from cutting round ingot in square slabs) not included in Cz-process but in Wafering process.

production chain. This selective choice for low-carbon electricity usage in European production may distort a fair country comparison. Hence, this study ensures a fair comparison by using the respective average grid electricity mix in Ecoinvent v3.7 for the production chains in all production locations. These electricity mixes, although the most up-to-date grid mix inventories available, are based on the year 2012 for China and 2017 for Germany and for the EU, and have a carbon intensity of 1 023, 582 and 405 g CO_2-eq/kWh, respectively, in Ecoinvent v3.7 [22]. The implications of these outdated electricity mix inventories for the results will be discussed in section 3.3. Transport is only modelled for finished modules since the whole PV process chain, including selected intermediate products, are assumed to take place in one single production location in China, Germany or the EU. The finished modules, including packaging, are transported by train, truck and, in the case of China, ship from the production location to an average European installation location (irradiation: 1391 kWh/(m^2yr)). Transport is based on weight of packaged modules (tkm), consistent with the common modelling approach of transportation in Ecoinvent [22] and PV LCA reports [3,29,47,56], and can be viewed in the SI.

2.3. Sensitivity analysis

2.3.1. Impact of module materials

Sensitivity analysis is a key component of LCAs, helping to understand the influence of assumptions and parameters on the outcome of the study [7]. Corresponding to the focus of this study on module design, its sensitivity analysis focuses on module materials as well as selected other factors with potentially large impact. The sensitivity analysis is carried out for both module designs, G-G and G-BS modules, but only for production in Germany, in order to simplify the discussion. Similar sensitivities are expected for production in the EU and China. Each factor (wiring, backsheet, EVA, glass, frame, wafer, module efficiency and total energy requirements) is increased or reduced by 10%.

2.3.2. Impact of life cycle inventory

Existing PV LCA studies mostly use Ecoinvent [22] and IEA PVPS 2015 [3] as LCI sources, see overview in Table 2, while the latest LCI update by IEA PVPS in 2020 [29] has not yet been frequently taken up. Although many studies acknowledge the outdated nature of these inventories in the context of rapidly improving PV technologies and try to compensate this by individually adjusting certain parameters, such as module efficiency or wafer thickness [45–47,49], there is no coherence in the adjustment approach, resulting in limited comparability between studies [21]. Moreover, key parameters, such as energy and material consumption in the production chain, are rarely updated although industrial roadmaps show significant savings in production since the years of data acquisition for these LCIs [23,33]. This paper aims to provide some clarity on the influence of using different LCIs by comparing the potential environmental impacts associated with Ecoinvent v3.7 [22], IEA PVPS 2015 [3] and the current, production-based LCI of this study. The most important differences in parameters and assumptions of these inventories are listed in Table 4. Moreover, this sensitivity analysis aims to unveil how module efficiency and source of electricity mix in these commonly used LCIs influence the results, highlighting the significance of modifications to these parameters. To this end, this sensitivity analysis not only compares the (1.) original Ecoinvent and PVPS 2015 LCIs with this study but also these two LCIs adopted for (2.) current module efficiencies, (3.) average electricity mix instead of selective electricity sources as given in Table 4 and (4.) current module efficiencies and average electricity mix. This LCI comparison is carried out for glass-backsheet modules produced in the EU since all three inventories include this module design and production location.

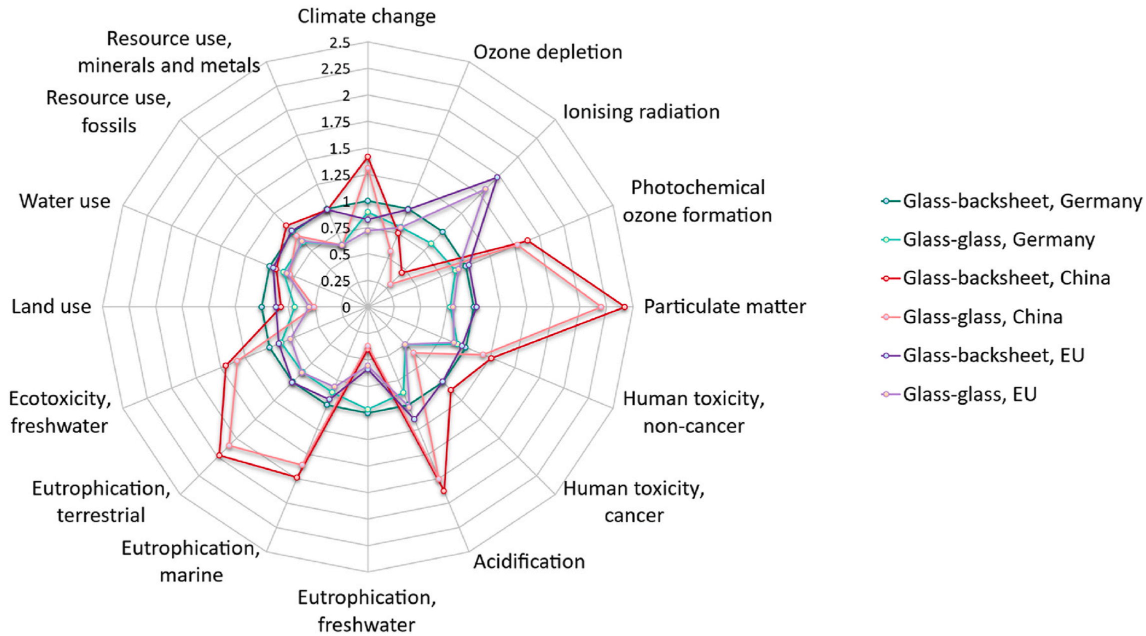

Fig. 3. Results of environmental assessment of 1 kW_p sc-Si glass-backsheet and glass-glass modules produced in China, Germany or the EU for the 16 EF environmental indicators recommended by IEA PVPS and EU PEFCR [13,14]. Glass-backsheet modules: P = 366 W_p, η = 19.79%. Glass-glass modules: P = 359 W_p, η = 19.40%. Including production, transport and end-of-life. Excluding BOS, installation and operation. Results of glass-backsheet modules produced in Germany are scaled to 1. Absolute values are given in SI.

3. Results

3.1. *Environmental impacts per* kW_p *nominal power*

The results of the environmental assessment per kW_p nominal power of glass-backsheet and glass-glass modules produced in China, Germany or the EU are shown in Fig. 3. For all impact categories and for all manufacturing locations, the G-G design shows lower impacts than the G-BS design, despite the slightly higher reference flow due to lower module efficiency. The modules produced in China exhibit lower impacts than those produced in Germany or EU for the impact categories ozone depletion, ionising radiation, freshwater eutrophication, land use and water use. For the other impact categories, module production in Germany has a lower impact than in China, and module production in EU is slightly lower or similar to Germany, with the exception of ionising radiation. The differences in results for each environmental impact category are mainly caused by the different composition of the countries' electricity mixes. For example, the higher results for German production for land use and water use are caused by the high share of biogas and the higher results for German production for freshwater eutrophication are caused by the high share of lignite coal in the German electricity mix. Conversely, the higher results for Chinese production for particulate matter, acidification, terrestrial and marine eutrophication and freshwater ecotoxicity are caused by the high share of hard coal in

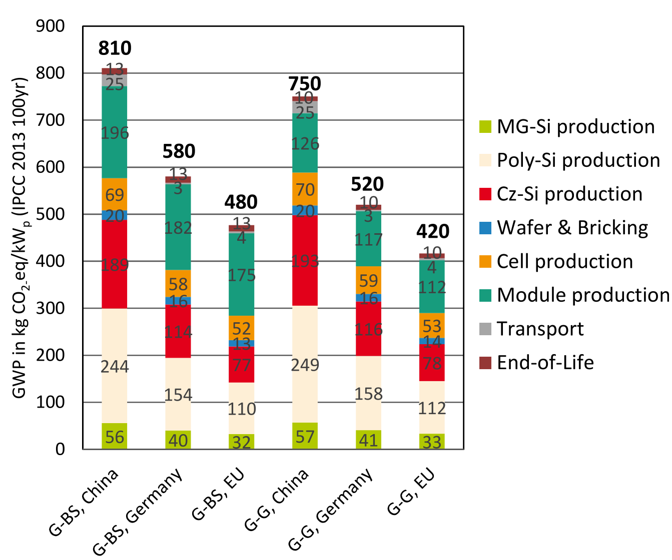

Fig. 4. Climate change: Global Warming Potential (GWP) in kg CO_2-eq/kW_p for sc-Si glass-backsheet (G-BS) and glass-glass (G–G) modules produced in China, Germany or the EU using IPCC 2013 100-year method. Including production, transport and end-of-life. Excluding BOS, installation and operation. Glass-backsheet modules: P = 366 W_p, η = 19.79%. Glass-glass modules: P = 359 W_p, η = 19.40%. LCI listed in SI.

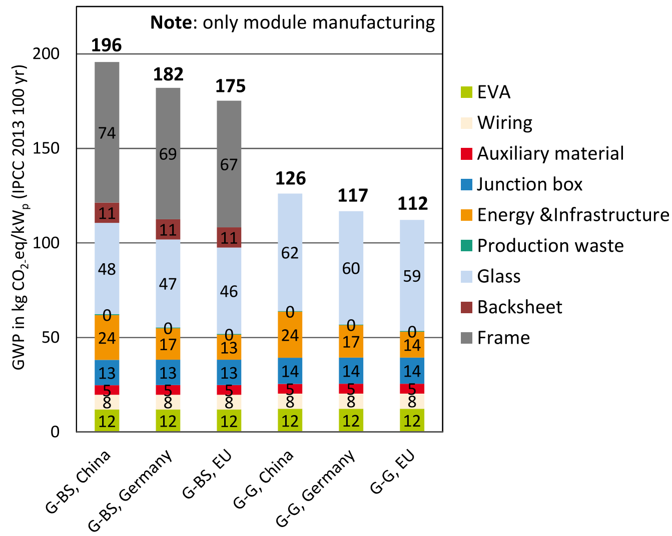

Fig. 5. Climate change: Global Warming Potential (GWP) in kg CO_2-eq/kW_p for module manufacturing for sc-Si glass-backsheet (G-BS) and glass-glass (G–G) modules produced in China, Germany or the EU, respectively, using IPCC 2013 100-year method. Only the impact of module manufacturing are shown, excluding cells. Aluminium and glass are produced using regionalized electricity mixes. Glass-backsheet modules: P = 366 W_p, η = 19.79%. Glass-glass modules: P = 359 W_p, η = 19.40%. LCI listed in SI.

the Chinese electricity mix. Results for ionising radiation are especially high for the EU because of the high share of nuclear power in the European electricity mix. The indicator resource use (mineral and metals) is identical for all production locations because production and, hence, the absolute amount of minerals and metals contained in the PV modules is modelled identical in each location. It needs to be noted, however, that the results for some impact categories may not be fully representative of current production as the inventory by Ref. [30], which is used in this study, did not obtain current industry data for the emissions along the production chain and, instead, approximated these with the emissions in Ecoinvent, which go back to PV production in 2005 [22].

Concerning climate change, Fig. 4 shows that glass-backsheet (glass-glass) modules produced in China, Germany or the EU are linked to emissions of 810 (750), 580 (520), and 480 (420) kg CO_2-eq/kW_p, respectively. These results illustrate that production in Germany and the EU causes approximately 30% and 40% less greenhouse gas (GHG) emissions than in China, respectively. Moreover, it shows that G-G design has a smaller carbon footprint than G-BS design (8% less in China, 11% less in Germany and 12.5% less in the EU).

The carbon emissions associated with the different module components, excluding cells, are shown in Fig. 5. Aluminium used for the frame makes up the highest share, followed by glass, while all other components are below 3% of total CO_2-eq emissions. The elimination of the aluminium frame in the G-G design is the main cause for the reduced emissions compared to the G-BS design, while the additional CO_2-eq emissions by the higher glass usage in the G-G design are almost compensated by not requiring a polymer backsheet.

The relative contributions of the processing steps, module components and electricity to the final GHG emissions are depicted in Fig. 6, with the width of the flow corresponding to the magnitude of emissions. Electricity is the major driver of carbon emissions throughout the entire process chain (52%–69%), while other upstream process inputs have only little impact (12–23%). The most emission-intensive steps are polysilicon and Cz-crystal production due to their high electricity

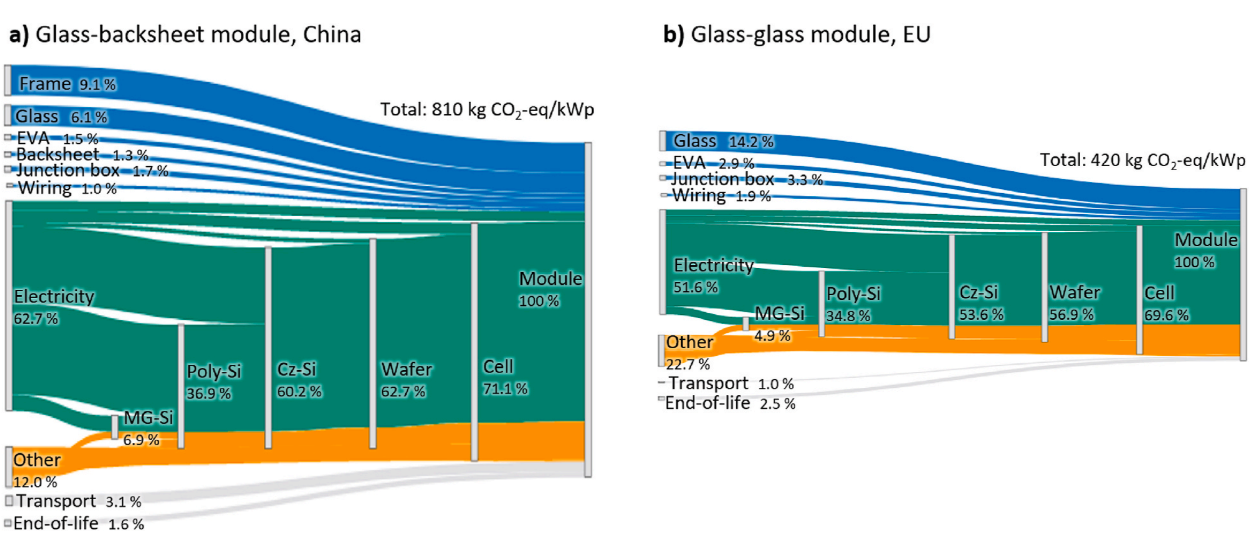

Fig. 6. Climate change: Sankey diagram of percentual contributions of module production steps, module components and electricity to the indicator Global Warming Potential (GWP) using IPCC 2013 100-year method for 1 kW_p of glass-backsheet sc-Si PERC module (P = 366 W_p, η = 19.79%) produced in China (a) and glass-glass sc-Si PERC module (P = 359 W_p, η = 19.40%) produced in EU (b). The other cases are shown in the supplementary information. Including production, transport and end-of-life. Excluding BOS, installation and operation. Thickness of flows corresponds to magnitude of emissions. LCI listed in SI.

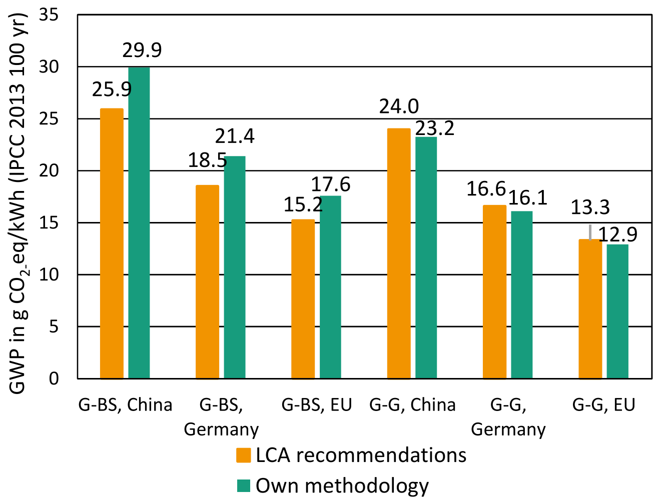

Fig. 7. Climate change: Global Warming Potential (GWP) in g CO_2-eq/kWh of sc-Si glass-backsheet and glass-glass modules produced in China, Germany or the EU using IPCC 2013 100-year method. Including production, transport and end-of-life. Excluding BOS, installation and operation. Installation location is an average European location (1391 kWh/(m^2yr) solar irradiation). Orange: calculation based on recommendations of IEA PVPS 2020 for LCA of PV systems (LT = 30 yr, PR = 0.75, DR included in PR). Green: calculation based on own methodology using average of module performance warranties given by PV module producers (LT = 25.44 yr (G-BS), 29.89 yr (G–G), PR = 0.85, $DR_{1st\ year}$ = 2.67% (G-BS), 2.55% (G–G), $DR_{following\ years}$ = 0.64% (G-BS), 0.45% (G–G). Including production, transportation and end-of-life; excluding BOS, installation and operation. LCI listed in SI. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

requirements. Transport accounts for approx. 3% for the Chinese production, with transoceanic ship transport as the largest contributor, while transport makes up 1% for production in the EU and Germany. At end-of-life stage, the material recovery of frame, glass and cabling yields environmental benefits, yet the recycling process also requires energy and the incineration and landfilling of the polymer and silicon components entails emissions. The results show that these burdens of the modelled recycling slightly outweigh the benefits, leading to a small net contribution of end-of-life stage to the overall carbon emissions (1.6–2.5%). It needs to be noted that silicon is not recycled in this inventory and that future high-yield recycling of silicon is expected to create further environmental benefits [57].

3.2. Carbon footprint per kWh produced electricity

The GHG emissions per kWh of produced electricity, excluding BOS, are shown in Fig. 7, ranging from 13.3 to 25.9 g CO_2-eq/kWh based on calculation method by LCA guideline [13] and from 12.9 to 29.9 g CO_2-eq/kWh based on our own calculation method using module power warranties. For both calculation methods, the carbon intensity of modules produced in Germany is lower than in China, while EU is the lowest. Moreover, the carbon intensity of G-G modules is lower than of G-BS modules in each production location. However, the difference between the two module designs is more pronounced when using real-world warranty data (25% reduction for G-G compared to G-BS modules in Germany) than when following LCA recommendations (10% reduction for G-G compared to G-BS modules in Germany). This is because the 438 evaluated warranties assume different average lifetimes (25.44 years for G-BS and 29.89 years for G-G modules) and different average degradation rates (0.64% vs. 0.45%), whereas the LCA guideline does not account for differences in system performance parameters between different crystalline silicon PV module designs [13], see Table 3. Interestingly, the use of module warranty data leads to higher carbon footprints per kWh for G-BS modules than when using the LCA recommendations because the warranted degradation rate for G-BS modules is relatively high (0.64%/yr) and the warranted service lifetime is much lower (25.4 instead of 30 years), leading to lower lifetime electricity generation.

As BOS is required to produce electricity, a full assessment of impacts per kWh of produced electricity needs to add the emissions of BOS, too. For example, [30] calculates the carbon footprint of BOS based on Ecoinvent v3.6 to amount to 8 g CO_2-eq/kWh, when produced with the European electricity mix, and 17 g CO_2-eq/kWh, when produced with the Chinese electricity mix.

3.3. Sensitivity analysis

3.3.1. Module materials

Fig. 8 shows the results of the sensitivity analysis for 3 of the 16 environmental impact categories (all results are given in the SI). Both module designs show similar results for the sensitivity analysis because of their similar material composition, except the higher glass consumption and lack of frame and backsheet in the G-G design. Some factors have a high influence on all impact categories, e.g. module efficiency, due to the linear decrease of required module area with increased efficiency. Other factors, e.g. backsheet and EVA, have a relatively low influence on all impact categories, indicating their low relevance for potential environmental improvements. Moreover, most

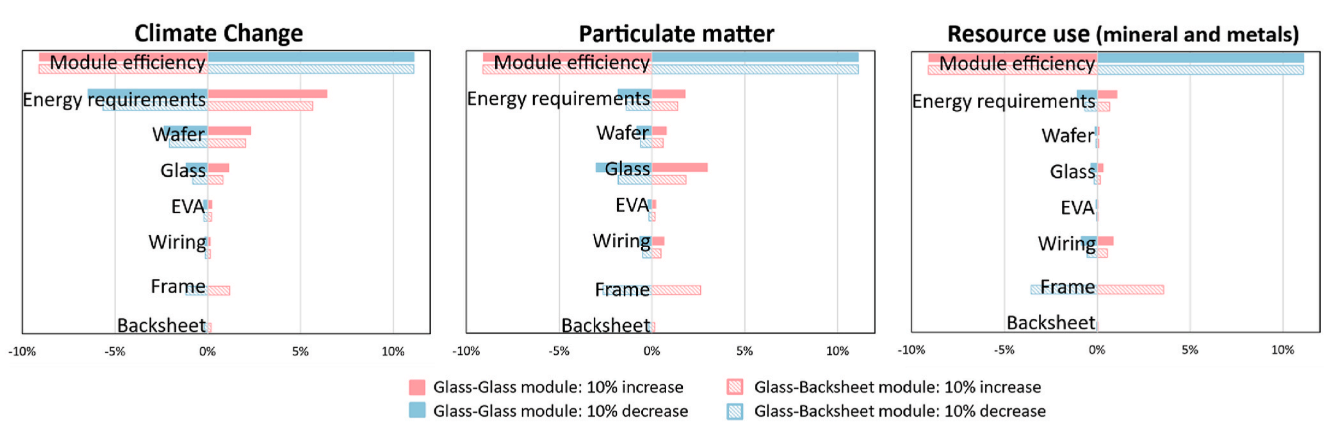

Fig. 8. Sensitivity analysis of various module parameters for the impact categories climate change, particulate matter and resource use (mineral and metals) for glass-glass and glass-backsheet modules produced in Germany. Each parameter is increased or reduced by 10%. The results indicate the percentual changes of the overall impact for the environmental indicator. The plot for module efficiency is asymmetric because the calculation divides by this parameter, resulting in non-linearity. Results for the other 13 impact categories are given in the SI.

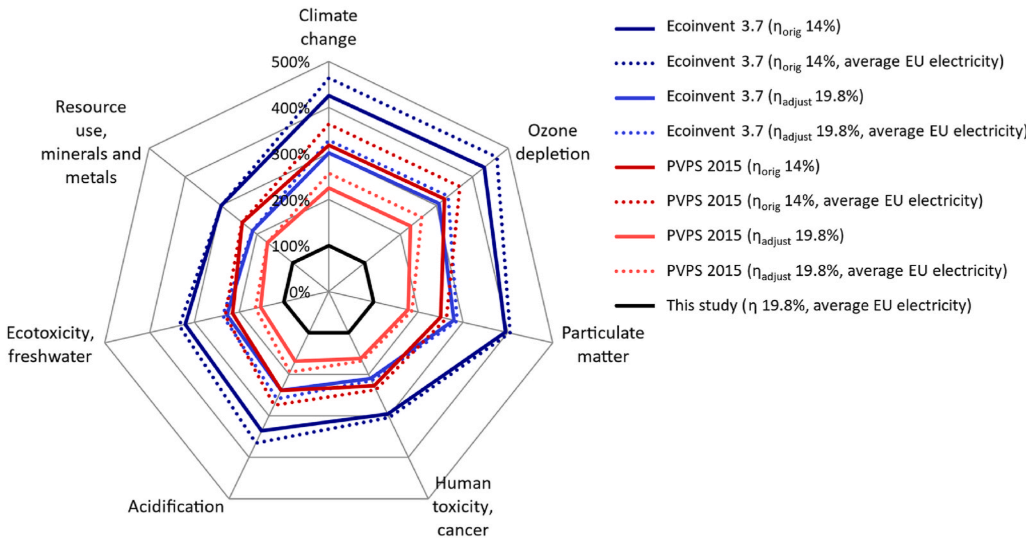

Fig. 9. Comparison of glass-backsheet (G-BS) modules in this study with publicly available LCIs: Ecoinvent v3.7 [22] and IEA PVPS 2015 [3] for selected environmental impact categories. The results for all 16 impact categories and absolute values can be found in the SI. For simplification, only G-BS modules produced in the EU were compared. BOS, installation, transport and end-of-life are excluded. Blue lines refer to Ecoinvent v3.7, red lines to PVPS 2015, black line to this study. Darker shades have original module efficiency ($\eta_{orig.}$ = 14%), lighter shades have module efficiency adjusted to this study's ($\eta_{adjust.}$ = 19.8%), dashed lines have harmonized electricity sources (average European electricity mix of the year 2017) instead of various sources as listed in Table 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

factors show a varying impact for different environmental impact categories, e.g. 10% reduction in energy requirements leads to 5.7–6.4% reduction in climate change but only 0.7–1.0% reduction in resource use (minerals and metals). This underlines the importance of a comprehensive analysis of the contribution of materials to different impact categories, which is necessary to identify and avoid possible shifts of burden from one impact category to another. Concerning climate change, the sensitivity analysis identifies module efficiency, process energy requirements, wafer thickness, frame and glass as the most influential factors.

3.3.2. Comparison of life cycle inventories

The sensitivity analysis shows that the choice of life cycle inventory data and potential adjustments to these has a significant impact on the final potential environmental impacts, as shown in Fig. 9 for selected impact categories. Concerning climate change, using the original Ecoinvent v3.7 and PVPS 2015 LCI causes 4.3 times and 3.2 times higher emissions than in this study, respectively. Substituting the selective choice for low-carbon energy during some production steps in Ecoinvent v3.7 and PVPS 2015 inventories with the average European electricity mix throughout the entire production results in a further slight increase in impacts for both datasets, see dotted lines in Fig. 9. Adjusting the module efficiency to current values (η_{orig} 14% to η_{adjust} 19.8%) reduces the difference in emissions to 3.0 and 2.3 times the GHG emissions of this study for Ecoinvent v3.7 and PVPS 2015 LCI, respectively. The large remaining gap in emissions between the module-efficiency-adjusted publicly available life cycle inventories and this study stems from the significant reductions in material consumption and energy consumption along the process chain as listed in Table 4, which are caused by the technological developments of recent years [23], mainly driven by a reduction in silicon consumption. This shows that merely adjusting the module efficiency of older LCIs to current levels without revising material and energy consumption along the process chain is insufficient to model the current environmental impacts of PV systems.

4. Discussion

In view of the urgency for climate action and the limited length of this paper, only the impact category climate change is discussed in detail.

4.1. Impact of module designs

Despite slightly higher material consumption due to lower module efficiency, glass-glass modules show lower environmental impacts per kW_p than conventional glass-backsheet modules, mainly because of the elimination of the aluminium frame. The better environmental performance of G-G modules is further enhanced for the lifetime electricity production (impact per kWh), if the longer potential lifetime and lower degradation rates of G-G modules [32] are used in the yield calculation, approximated with the real-life power warranties in this analysis. This emphasizes the need to assess not only the influence of module design choices on material and energy savings in production (leading to reductions per kW_p) but also to critically investigate the impact of these design choices on system performance (leading to further reductions per kWh). Yet, the standardized yield calculation method as recommended by IEA PV LCA guideline [13] does not account for the better system performance of glass-glass module designs, concealing the potential reductions in emissions per kWh due to higher, design-specific electricity yields.

The only comparison of glass-glass and glass-backsheet module designs found in the literature by Luo et al. [34] finds 821 kg CO_2-eq/kW_p and 29.2 g CO_2-eq/kWh for multi-crystalline silicon (mc-Si) glass-backsheet modules and 767 kg CO_2-eq/kW_p and 20.9 g CO_2-eq/kWh for mc-Si glass-glass modules, including BOS, see Table 2. Yet, their analysis uses a relatively high DR for G-BS modules (1%/year) and low DR for G-G modules (0.2%/year), which may not be representative for the technologies. Moreover, they only consider multi-crystalline silicon, not single-crystalline silicon, do not account for recent improvements in the PV production and assume production to take place in Singapore [34]. As the electricity mix in Singapore emits only 485 g CO_2-eq/kWh and multi-crystalline silicon is less energy intensive than single-crystalline silicon, their results are still in the same magnitude as in this study (420–810 kg CO_2-eq/kW_p and 13–30 g CO_2-eq/kWh, excluding BOS), although their LCI does not account for the recent technological developments and includes BOS. If sc-Si was used and the different assumptions were harmonized, the results of [34] would be significantly higher than this study.

4.2. Impact of production location

As the majority of carbon emissions is caused by the electricity consumption during production (see Fig. 6), the carbon intensity of the electricity mix at production location is one of the highest levers for reducing the carbon footprint of PV systems [20,21,40,58]. Although the energy intensive silicon production should ideally take place in countries with low-carbon electricity mixes [40], China, which has a carbon-intensive coal-based electricity mix, dominates the market by producing 68% of polysilicon, 96% of wafers, 76% of cells and 71% of PV modules in 2019 [38]. Given the dominance of production in China, geographically representative inventories based on Chinese companies need to be developed [47], contrasting the predominantly European data sources in Ecoinvent v3.7 [22] and IEA PVPS 2015 [3].

A partial shift of production to regions with low-carbon electricity mixes, decarbonization of the Chinese electricity mix [28,43,59,60] or production of selected high-energy intermediate materials in low-carbon regions are potential options for improvements. This study shows that the carbon emissions from transportation of final modules from China to Europe are small compared to the additional carbon emissions caused by production in China, a finding supported by other studies [27,28,30,47]. Thus, it can be concluded that transcontinental transport of selected high-energy precursor products is expected to be negligible in comparison to the savings from using a low-carbon electricity mix. Most savings can be achieved by relocating the production of polysilicon and Cz-crystal, the most energy-intensive precursor products, see Fig. 6.

Finally, a discussion of the impact of the electricity mix in producing countries is incomplete without also drawing attention to the importance of the electricity mix in the country of installation. Although the GWP of the total PV system is independent of the electricity mix in the country of installation as PV systems do not notably consume electricity during operation, the actual carbon savings achieved by a PV system lie in the difference between the carbon intensity of the replaced electricity mix at the installation location and of the PV electricity. Thus, maximum GHG emission savings can be achieved when PV systems are produced in low-carbon locations and installed in locations with a carbon-intensive electricity mix and high solar irradiation [40,61].

4.3. Recommendations for future studies

As the comparison of the PV LCIs from Ecoinvent, IEA PVPS 2015 and this study has shown, the commonly used inventories fail to reflect the current state-of-technology, and, even if adjusted for increased efficiencies, still overestimate the environmental impacts of current PV systems by a factor of 2.3 or more. The recently published IEA LCI update in 2020 [29] can be seen as a long-awaited response to the need for current, high-quality and publicly available LCI for PV technologies [48, 62]. The comparison of inventories also emphasizes the need for LCA practitioners to critically engage with the published inventories and to avoid updating old inventories with superficial modifications only. As PV technologies are expected to continue to undergo significant technological improvements [23], public LCIs ought to be regularly and systematically updated to reflect these dynamic future improvements [21].

For an analysis of regionalized production, the exact modelling of the electricity mixes is vital. This study uses the average medium voltage electricity mixes for China, Germany and EU as given in Ecoinvent v3.7, which are based on the year 2012 for China and 2017 for Germany and the EU, and emit 1 023, 582 and 405 g CO_2-eq/kWh, respectively [22]. Recent estimations, however, project the direct carbon intensity for the German electricity mix at 401 g CO_2-eq/kWh for 2019 [63] and for the Chinese electricity mix at 821–861 g CO_2-eq/kWh for 2020 [64]. Although these sources only include direct and not indirect emissions, the trend for the total CO_2-intensity can be expected to have decreased, too. If current, lower carbon-intensities of the electricity mixes were used, the resulting carbon emissions of PV systems in this study would be even lower [65–67]. Since 52–69% of the greenhouse gas emissions of the investigated PV systems stem from the electricity used in the PV production processes, the carbon intensity of the used electricity mix has an immediate influence on the overall results. Hence, this study flags outdated electricity mixes as a source for overestimation of emissions for PV and motivates future studies to conduct LCAs on PV systems with current electricity mixes. It also calls for more frequent updates of country-specific electricity mixes in LCA databases to keep track of the emission reductions in the electricity sector.

Despite official methodological guidelines [13] and the harmonization efforts by the scientific community [21,24], the results of existing PV LCAs remain difficult to compare, see Table 2. While supporting the general need for a more harmonized LCA approach for PV technologies, this study advocates that these harmonized methodologies need to be differentiated enough to account for actual technology- and design-specific differences, such as different lifetime electricity yields of crystalline silicon glass-glass and glass-backsheet modules as demonstrated in this study. Such differentiated guidelines can coherently incentivise the development of more environmentally friendly modules designs.

5. Conclusion

This study investigates the life cycle environmental impact of two different single-crystalline silicon (sc-Si) PV module designs, glass-backsheet (G-BS) and glass-glass (G-G) modules, produced in China, Germany or the EU using current inventory data. Results for all environmental impact categories are lower for the G-G design compared to the G-BS design, while most indicators show lowest values for production in the EU, followed by Germany and China. Concerning climate change, the glass-glass design has a smaller carbon footprint than the glass-backsheet design (8% less in China, 11% less in Germany, 12.5% less in EU) and both module designs emit 30% and 40% less carbon when produced in Germany and the EU compared to China, respectively. This study shows that glass-glass modules have a better environmental profile than glass-backsheet modules, especially if their higher lifetime electricity yield is taken in account. As the mounting structure, which is part of the balance of system (BOS), has been excluded in this study, further research needs to investigate how the different requirements for mounting structures of the two designs influence this comparison.

As this study uses state-of-the-art industry data concerning cell efficiency, wafer thickness, kerfloss, energy and material requirements during production, its results are considerably lower than previous LCAs of sc-Si PV systems that rely on older data. With a carbon footprint of 420–810 kg CO_2-eq/kW_p and 13–30 g CO_2-eq/kWh (excluding BOS), this study shows that current sc-Si PV modules are indeed a low-carbon pillar of the energy transition, emitting even less carbon than previously expected. The comparison of the most commonly used life cycle inventories (LCIs) (Ecoinvent v3.7 [22] and PVPS 2015 [3]) with this study reveals the significant achievements in emission reduction in PV module production in the last 10 years. Simultaneously, it demonstrates that modelling current PV technologies with these established LCIs and only superficially adjusting some technical PV parameters (e.g. module efficiency and wafer thickness), as frequently done in the literature, leads to significant overestimation of the potential environmental impacts. Thus, a critical examination of available LCIs by LCA practitioners and current, high-quality and publicly available LCIs for the PV value chain are vital. In addition, more frequent updates of country-specific electricity mixes in the major databases are important.

This study identifies the energy requirements during silicon processing, material consumption, e.g. by thinner wafers and less kerfloss, and module efficiency to have the highest impact on GHG emissions. Future research should specifically target improvements in these parameters. Module design variations, such as glass-glass modules, can reduce GHG emissions not only by reducing material and energy requirements during production but also by improving system performance, e.g. by longer lifetime or reduced degradation rates, and, thus, providing higher lifetime electricity yields. These design-specific differences need to be anchored in LCA guidelines for PV systems to account for the actual differences in emissions and to incentivise the development of environmentally friendlier module designs.

Author contribution

Amelie Müller: Conceptualization, Investigation, Formal analysis, Methodology, Visualization, Writing – original draft. Lorenz Friedrich: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing. Christian Reichel: Investigation, Validation, Supervision, Writing – review & editing. Sina Herceg: Conceptualization, Investigation, Methodology, Validation, Supervision, Writing – review & editing. Max Mittag: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. Dirk Holger Neuhaus: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solmat.2021.111277.

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