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Global warming potential of photovoltaics with state-of-the art silicon solar cells: Influence of electricity mix, installation location and lifetime

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ABSTRACT

Efforts are driven to fast-track energy transition for more energy security, resilience, and affordable energy for all. A major objective in implementing the transition to renewable energies is the overall reduction of the global warming potential (GWP). Therefore, it is important to investigate key parameters that can reduce the GWP of renewable energy technologies even further. In this study, the GWP of a state-of-the-art, market-dominating passivated emitter and rear cell (PERC) in a glass-backsheet photovoltaic (PV) module based on Czochralski (Cz) grown silicon wafers is explored to determine the influence of up-to-date electricity mix of the production location, the installation location as well as the lifetime. This comprehensive analysis showed a GWP reduction potential of approximately 62% only through strategic planning of the upstream production location of each life cycle phase. Additionally, approximately 58% of the GWP reduction potential is observed by changing the downstream installation location and lifetime of the PV modules. Furthermore, this study promotes and provides guidelines for modelling the correct electricity mix in the correct voltage composition, which is important to precisely portray time representativeness of the grid electricity in LCA of any production process but rarely used in practice. Lastly, the study provides opportunities for solar cell manufacturers to create a more sustainable product by strategically reducing their product's GWP through changes in the electricity mix of the supply chain location.

1. Introduction

With a goal to limit global warming to well below 2, preferably 1.5 °C, compared to pre-industrial levels, the Paris agreement called to make finance flows consistent with a pathway towards low greenhouse gas emissions [1]. This has led to the development of the global warming potential (GWP) indicator *Climate Change* [2]. The GWP enables the comparison of the global warming impacts of different gases such as CO_2, methane (CH_4), nitrous oxide (N_2O), etc. [3]. Measured in kg CO_2-eq., the GWP helps to combat climate change by revealing the greenhouse gas (GHG) hot spots from the life cycle of the product and subsequently, directing efforts towards improving the system.

According to recent scenarios, the GWP of the EU electricity sector is expected to show one of the most significant reductions by 2030 of at least 55% compared to 1990 and net climate neutrality by 2050 [4]. Solar photovoltaics (PV) is a promising technology to reach this ambitious goal and is anticipated to play a prominent role in future global energy systems based on renewable energy resources [5]. In the field of photovoltaic solar cell technology, the 'Passivated Emitter and Rear Cell' or 'Rear Contact' (PERC) cell technology was the global market leader holding 80 % of market share in 2020 [6]. The sudden outbreak of the COVID-19 pandemic in 2019 led to the implementation of stringent lockdown regulations across several nations and resulted disruptions in import and export activities of photovoltaic modules. But even through the crisis, the photovoltaic market grew at a steady rate with the rising adoption of strategies by key players [7]. The demand of photovoltaics is increasing continuously owing to urbanization and growing global energy demand. Moreover, the devastating Russo-Ukrainian war has created an energy crisis; dramatically increasing the need for energy independence within the European Union which is driving fast adoption of renewables. It is estimated that increased environmental regulations related to carbon emissions will

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also drive the demand of photovoltaics higher as the GWP of the solar cells is insignificant when compared to fossil fuel (Fig. 1).

Fig. 1, sourced from the latest Ecoinvent 3.9 database [8], shows the global (rest of the world [RoW] datasets) GWP of different energy technologies. The red (top) and green (bottom) points signify the maximum and minimum GWP values based on differences in technology specification and location. For oil, this difference is created due to different shares of heavy fuel oil used to produce electricity by different locations. On the other hand, within hydro technology, the pumped storage technology has significantly more GWP when compared to a run-of-river technology. Apart from this, within this database the GWP of PV (Ecoinvent 3.9 activity: electricity production, photovoltaic system, 3 kWp slanted-roof installation, single-Si, panel, mounted [RoW]) is shown as 90.3 g CO_2-eq./kWh which is ~14 times lower than lignite, ~12 times lower than hard coal and ~7 times lower than natural gas. However, recent GWP analyses show lower values for photovoltaics to what is shown in the Ecoinvent 3.9 [9].

Additionally, as observed from the analysis of Müller et al. [9], the production location of the PV system has significant impact on its GWP. What differs for every production location is primarily the electricity mix of that region and its associated GWP. The electricity mix is defined as the share of different energy generating technologies used to produce electricity for that specific location. The more the share of renewable energy in an electricity mix, the less is its GWP as renewable energy technologies produce less GHG emissions. As shown by Müller et al., the electricity used in production can have up to 62.7% and 51.6% of the GWP impact respectively for a glass-backsheet module produced in China and glass-glass module produced in Europe [9]. Therefore, the electricity mix is of high interest when investigating the reduction potential in GWP. Hence, an investigation on GWP reduction potential of the upstream phase for switching PV system production to a location with more renewables in the electricity mix is necessary.

In addition to this, two challenges are often faced by LCA practitioners when choosing “electricity” from the database. Firstly, an electricity mix for the present year of study is unavailable in Ecoinvent database, compromising time representativeness of the study unless updated to current statistics by practitioners. And secondly, the database includes electricity in high, medium and low voltage levels but does not include the net electricity dataset which is actually used in production. Both challenges impact the accuracy of the study. In an effort to tackle these issues, this paper demonstrates the implementation of electricity mixes of latest available year and creation of a *net electricity* model.

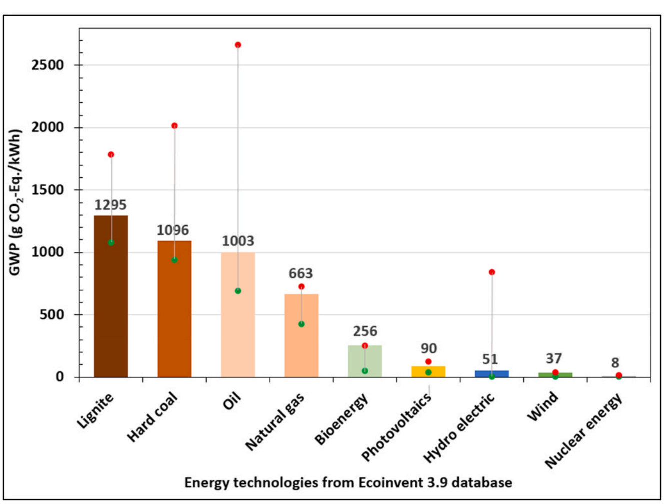

Fig. 1. Global Warming Potential (GWP) in g CO_2-eq/kWh of different electricity producing technologies sourced from LCIA documentation of Ecoinvent 3.9 available in Ecoquery. Red (top) and green (bottom) points signify the maximum and minimum GWP values respectively, as shown by Ecoinvent for each technology.

On the downstream side of the PV value chain, the installation location of the PV system has a significant impact on its GWP, which is primarily due to the difference in solar irradiation. With regards to temperature losses, higher irradiation on the modules plays a vital role in improving the energy yield performance of a PV system, and subsequently, the GWP in kWh of electricity generated. In addition, a longer PV system lifetime increases the lifetime energy yield. So, it is also worth analysing the impact of different location of installation, along with lifetime of the PV system, to find more scopes to reduce the GWP and have a better idea of where PV installation is beneficial.

These GWP reduction opportunities of PV are often important for the manufacturers to improve their product. Of the different impact categories, GWP is commonly used in different market regulatory directives and environmental certificates such as the type III environmental declaration certificate known as the Environment Product Declaration (EPD) according to ISO 14025–2006 [10]. So, any improvement on the product can further support manufacturers to generate a certification, that is highly competitive in the market. Besides, knowledge on what influences the GWP of PV can also enable such green certification verifiers, researchers and consumers to correctly evaluate and compare different products. Therefore, the goal of this study is to assess the sensitivity of the GWP to the upstream (production) phase and the downstream (installation and use) phases. The analysis is based on a p-type M6 Czochralski grown silicon (Cz-Si) wafer and PERC system (without battery) previously analysed by Müller et al. [9]. An overview of the scope of the LCA in this work is illustrated in Fig. 2.

2. Methodology

2.1. Modelling of electricity mix and upstream life cycle phases

To visualize the impact of the share of different energy generating technologies used in a national electricity grid on the GWP, this paper considered three countries: China, Germany, and Norway. This location selection represents three very different grid electricity mixes. The influence of different shares of energy generating technologies in the electricity grid will be seen in its respective GWP and subsequently, on the GWP of the PERC system consuming this electricity for its production. The foreground model of the production process for the PERC PV module is modelled with the software Umberto v11 [11], using ‘allocation, cut-off by classification’ system model and the impacts assessment is based on the IPCC 2013 GWP 100a, with long term effects [12].

2.1.1. Calculation of share of different energy technology in the regional grid electricity mix and its GWP

As previously seen in Fig. 1, the GWP per kilowatt-hour of the fossil-based energy technologies is significantly higher than its renewable counterparts. Different countries use their individual share of energy generating technologies to feed its national electricity grid. Consequently, in countries or regions with higher shares of renewable technologies in the electricity mix the GWP footprint of products produced will be lower. Therefore, in this paper, we first analyse the electricity mix of the selected countries. For each country, the electricity mix is observed for the years presented in the Ecoinvent 3.7.1, Ecoinvent 3.8 and Ecoinvent 3.9 databases [8] as well as for the year 2020. Table 1 lists the data sources of the selected electricity mixes and shows the year for which the data has been collected. In previous publication Ecoinvent 3.6 [9] was used to calculate the GWP of solar modules. It is observed that the year represented in the Ecoinvent 3.8 database is 2014 for China sourced from China Electric Power Yearbook [13] and 2018 for Germany and Norway sourced from the International Energy Agency (IEA) [14]. So, in addition to location, this analysis work depicts us regarding how much the shares of different energy generating technologies, and subsequently its GWP, improved with the advancement of years for each location.

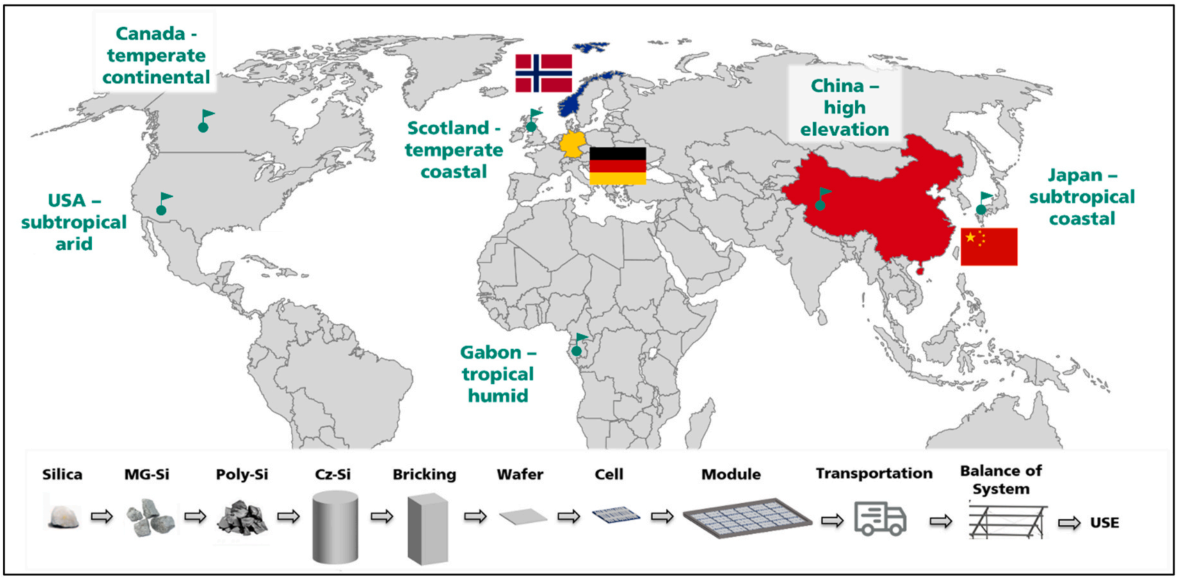

Fig. 2. Overview of the supply chain and the selected locations for the environmental assessment of PERC PV systems.

Table 1
Source of background data for the modelled net electricity mixes along with the representing year.

Electricity Mix (year)	Data Source	
China (2014)	Ecoinvent 3.7.1	market group for electricity, net [CN]
Germany (2017)		market for electricity, net [DE]
Norway (2017)		market for electricity, net [NO]
China (2014)	Ecoinvent 3.8	market group for electricity, net [CN]
Germany (2018)		market for electricity, net [DE]
Norway (2018)		market for electricity, net [NO]
China (2020)	Ecoinvent 3.9[a]	market group for electricity, net [CN]
Germany (2019)		market for electricity, net [DE]
Norway (2019)		market for electricity, net [NO]
China (2020)	Literature	CEC Statistics and Data Center [15]
Germany (2020)		Bruno Burger, Fraunhofer ISE [16]
Norway (2020)		Statistics Norway, SSB [17]

[a] Data obtained from "Electricity Analysis v3.9, Allocation, cut-off" documentation of Ecoinvent [8] as database was unavailable for Umberto software at the time of study.

In this analysis, the net electricity generation for all three locations are modelled using the high, medium and low voltage level electricity activities from Ecoinvent. Fig. 3 below provides an illustration on the calculation of a country's net electricity demand from high, medium and low voltage level [18]. In most LCA studies, the practitioner is found to use the medium voltage or low voltage electricity activity from Ecoinvent to represent the electricity fed into the factories at production. But usually, the factories are fed with the *net electricity* or *domestic supply* as shown by Itten et al. [18]. The medium and low voltage activities under-represent and over-represent the GWP, respectively, when compared to the net electricity. Medium voltage over-represents the GWP as in Ecoinvent only low voltage level includes photovoltaic technology while all other technologies including fossils are incorporated at the high voltage level activities. And low voltage under-represents the GWP as net electricity consumes only 64% of the produced electricity on the low voltage level [18].

In this study, the *net electricity* mixes of 2020 are modelled with the high, medium and low voltage activities of 'market group for electricity [CN]', 'market for electricity [DE]' and 'market for electricity [NO]' within the database Ecoinvent 3.8 as shown in Fig. 3. However, as the share of voltage level consumption is from 2009 and specific for the

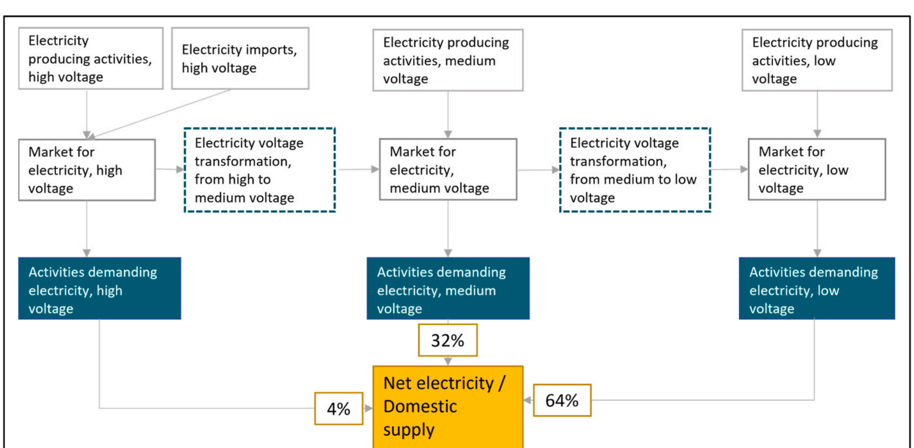

Fig. 3. Structure of and links between electricity markets (high, medium, and low voltage level) as modelled in Ecoinvent database v3. Activities enclosed in green includes voltage transformation losses incurred to transform high to medium followed by medium to low voltage levels. Sourced from Ecoinvent [8]. Demand of high, medium and low voltage electricity in the generation of net electricity as reported by Itten et al. [18] is shown in orange.

Swiss grid [18], it is recommended that future studies use shares from current year and specific locations to represent the electricity used for production.

On the other hand, to implement the 2020 literature net electricity shares within the Ecoinvent activities correctly, shares of all technologies, except PV obtained for low voltage level, need to be converted to the high voltage level. The share of PV is implemented at a later point. This is achieved using the voltage transformation loss factor. As shown in Fig. 3, in between the low voltage and the high voltage activities of Ecoinvent, three other activities are present namely 'electricity voltage transformation from high to medium voltage', 'market for electricity, medium voltage' and 'electricity voltage transformation from medium to low voltage'. Both transformation activities include the voltage transformation losses. These loss factors convert the shares of different energy technologies from low voltage level shares into its high voltage level shares, first from low to medium voltage level and subsequently from medium to high voltage level. By applying these loss factors, the shares of all the energy generating technologies in the high voltage levels are converted to represent the 2020 shares. In fact, to respect the model structures provided by the authors of the Ecoinvent datasets, this conversion is done keeping the transformation losses the same as modelled by Ecoinvent. Finally, the share of literature shares of PV is implemented on the low voltage level. Thus, the model in this work accurately represented the literature net electricity shares for the year 2020 in the Ecoinvent activities but divided in different voltage levels.

Of the three modelled countries, only the Ecoinvent electricity model for China does not include imported electricity. For Germany, the share of imported electricity for the year 2020 is taken from Reuters' report on German electricity statistics [19]. The share of import for Norway for the year 2020 is sourced from the Statistics Norway [17]. Furthermore, all electricity shares shown in Table 1 are net electricity generation shares except for the Chinese and Norwegian 2020 shares. For the shares of these two regions, it was unclear in the literature whether the shares represented net or gross electricity generation; here, net electricity generation was assumed for modelling due to lack of data. The share of lignite, nuclear and photovoltaics in gross electricity generation of Germany for 2020 was 16.2%, 11.3% and 8.7% respectively [20]. The same for net electricity generation was 16.6%, 12.8% and 10.5% respectively [16]. Therefore, although small, there is a difference between gross and net electricity generation. Hence it should be noted that, if the shares from literature shown for China and Norway for the year 2020 are indeed of gross electricity generation, then the precision of the comparison will be less accurate. Following this, the impact assessment is conducted using the Umberto 11 software to quantify the GWP.

2.1.2. *Life cycle inventory (LCI) of the PV module and system production*

The life cycle inventory (LCI) of the p-type M6 pseudo square (psq) wafer Cz-Si PERC PV system (without battery) chosen for this paper is sourced from Müller et al. [9]. In contrast to Müller et al. [9], this study included an advanced production scenario where electricity consumption for current production equipment and processes for Cz-ingot crystallization is calculated lower, with 25.1 kWh/kg-Si compared to regular scenario with 38.5 kWh/kg-Si. The same is found for wafering, 2.25 kWh/m^2 wafer compared to 2.35 kWh/m^2 of wafer of the regular scenario. This paper used the advanced scenario as we try to reduce the GWP even further. Similar to Müller et al., the approach of the life cycle analysis (LCA) in this paper also followed the framework presented in the ISO standards 14040–4 [21,22], the recommendations of the IEA PVPS 12 'Methodology Guidelines for LCA on PV' [23] as well as the Product Environmental Footprint Category Rules (PEFCR) for Photovoltaics of the European Union [24].

This attributional LCA includes the whole value chain of Cz-Si PV, starting with the production of metallurgical grade silicon (Mg–Si) from quartz and ending with the use phase and electricity generation of the PV System including the Balance-of-System (BoS) components. Excluded are the end-of-life stage, i.e., there is no recycling bonus or waste treatment process of the PV modules and the battery to store the produced electricity, as shown in Fig. 4. In contrast to the model by Müller et al., this study uses the Ecoinvent 3.8 database. The GWP is analysed for a functional unit (FU) of 1 kW peak of a PERC PV system and 1 kW h (kWh) of alternating current (AC) electricity generated by the PERC PV system.

To analyse the impacts of the electricity mix used in production on the GWP of the PV system, the electricity required to produce the PV system is categorized into foreground and background electricity. The foreground electricity is defined as the electricity required directly to produce different components of the PV system by the manufacturer such as solar cell production or module frame production. The background electricity is defined as the electricity required by the PV system indirectly to produce background materials in the background processes such as oxygen and nitrogen production. For instance, the electricity required to produce the aluminium alloy which is directly needed for the frame of the PV is considered foreground electricity. On the other hand, the electricity required for the *aluminium ingot production* required for the *aluminium alloy production* is considered background electricity. For feasibility of this study only the foreground electricity is modelled and replaced with the 2020 electricity mix for different locations while the background electricity is left unchanged. The foreground electricity is to be 33% of the cumulative energy demand for the production of a PERC PV system when calculated for a grid efficiency between 32% and 38%. This will give the readers a clear conception regarding the sensitivity of the PERC GWP to a change in the production location, i.e., using a different electricity mix. However, to reveal the influence of an updated electricity mix for the whole production and the complete underlying value chains for all ingoing production materials and their precursors the foreground as well as the background electricity must be considered [25].

2.2. *Modelling the PV system use phase*

The annual electricity generation or energy yield (E_{Agen}) represents the number of kilowatt hours produced in a year by a specific PV system including degradation. It is expressed in units of kWh. The solar irradiation is the most important parameter for the energy yield of the PV system besides the module efficiency [26]. In addition to solar irradiation, the energy yield is dependent on the angle at which sunlight is captured by the PV module and is therefore, dependent on the region of the globe and time of year [27]. With respect to temperature losses, the higher the irradiation of a location, the higher is the energy yield. And GWP is directly dependent on energy yield in kWh of electricity and therefore, the higher the energy yield, the lower will be the GWP of the PV system. To put this concept into test, this paper selected 6 locations, the annual global in-plane irradiation of which ranges from 2295.5 kWh/m^2 to 972.9 kWh/m^{2}a as shown in Table 2.

The energy yield calculations are based on a model that was developed to create a "virtual" Climate Specific Energy Rating (vCSER) [28] in agreement with the IEC 61853 [29–32]. The input parameters required are not measured but are simulated using the module geometry and the physical properties of its individual components. The model takes the angular losses, the spectral response and the heat transfer coefficients into account to determine the power of the PV module and calculate the energy yield per year.

For this assessment, an estimated 8% loss is included as system loss and capture losses for all locations. The system losses include inverter efficiency loss, interconnection losses, ohmic DC and AC cable losses as well as system up-time. Capture losses include horizon shading losses, shading by row losses and soiling losses (due to dirt on modules).

A list of parameters is provided in Table 3, where the degradation of the PERC PV system is calculated from the lifetime, guaranteed power after the 1st year and guaranteed power at end of life (EoL). To show the GWP reduction scope for an increase of lifetime of the PERC system, i.e.,

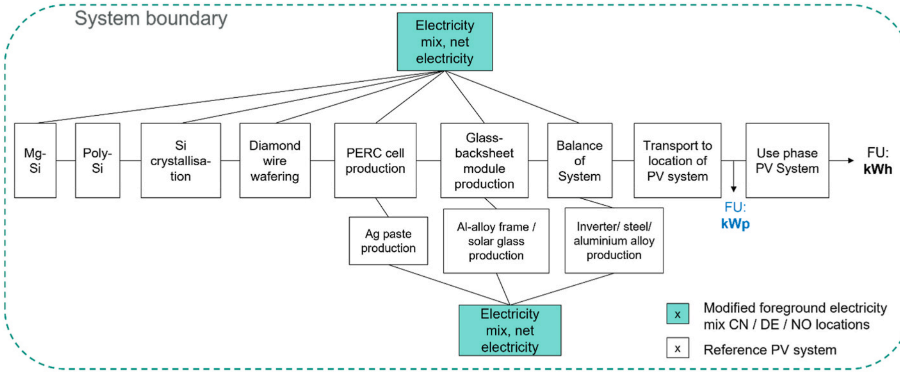

Fig. 4. System boundary of the LCA of PERC PV. Energy storage and end-of-life phase not included. The foreground electricity used (Green) is modified for the net electricity mixes of China, Germany and Norway. The background electricity is left unchanged.

Table 2
List of climatic datasets including the global in-plane irradiation (kWh/m^{2}a) and the latitude of the location.

Location	Latitude	Total yearly global in-plane irradiation (kWh/m^{2}a)
Subtropical Arid	33°33′N	2295
High Elevation (above 3000 m)	34°N	2139
Tropical Humid	1°S	1678
Subtropical Coastal	33°22′N	1497
Temperate Continental	57°N	1266
Temperate Coastal	56°N	973

Table 3
Key parameters of the p-type M6 psq wafer Cz-Si PERC module used.

Parameter	PERC (25 a)	PERC (30 a)	PERC (40 a)
Module area, (m^2)	1.83	1.83	1.83
Module efficiency (%)	20.11%	20.11%	20.11%
Lifetime (a)	**25**	**30**	**40**
Power after 1st year (%)	98%	98%	98%
Degradation following years (%)	0.54%	0.54%	0.54%
Guaranteed power EoL (%)	85.0%	82.3%	76.9%
Power at EoL (%)	**91.8%**	**90.4%**	**87.7%**

higher energy yield in kWh of electricity, the degradation is calculated for 25, 30 and 40 years [33] of lifetime. The GWP (g CO_2-Eq./kWh) of the PERC system, obtained from the software for PEFCR conditions [24], is divided by the energy yields obtained for the 3 different lifetimes, for each of the 6 different locations to derive the required results.

3. Results and discussion of the analysis

The results are divided into three sections. In the first section, the electricity mixes of the different locations are explored along with their resulting GWP. In the second section, results are presented for the GWP of the PERC system using the aforementioned electricity mixes as foreground electricity for its production. Finally, the sensitivity of the downstream parameters, installation location and lifetime of the PERC system, are explained.

3.1. Share of different energy technologies in the regional grid electricity and its GWP

In this study, the electricity mix of China, Germany and Norway, as shown in Fig. 5, are analysed in two aspects: Location and the year of data collection. Regarding the former aspect, all three locations presented its unique electricity mix. Approximately three-fourth of the electricity mix of China is based on coal. Among renewables, hydroelectric has the largest share, followed by wind. Both the Ecoinvent databases 3.7.1 and 3.8 represent the year 2014 for China and therefore, are the same. A similar picture is observed from the National Bureau of Statistics of China showing 78% of grid electricity generated from coal [34]. On the other hand, the electricity mix of Germany showed a moderate mix of technologies, approximately half generated by renewables. The renewables include high shares of wind, solar and biomass energy.

The net electricity mix modelled from Ecoinvent 3.8 shows that shares of PV for the years 2017 and 2018 in Germany are 7.4% and 8.4 % respectively. In contrast, the energy charts by Fraunhofer ISE shows 6.7% and 7.8% of PV for those years respectively [35]. We assume that this difference is due to the difference in consumption of low volage electricity in *net electricity* generation between the ISE energy charts and this study. As shown in Fig. 3, this study has used the shares of low, medium and high voltage electricity for *net electricity* specified for Switzerland for the year 2009 [18] as specific shares were not found, which can be different for other countries and current year. Lastly, over 95% of the electricity mix of Norway consisted of renewable energy, mostly hydroelectricity. It further included a small portion of thermal power which consisted of hard coal, oil and gas. Selection of these three locations ensured a wide range of electricity mixes which is intended to provide a clear conception regarding how much the GWP changes with the infiltration of renewables.

Regarding the latter aspect, the shares of technologies within each location has also changed over time towards an increasing renewable share and thus a lower GWP pathway. Looking into the Chinese electricity mix, it is seen that the share of carbon emission intensive coal technology in 2020 has drop by 13.3% when compared to the year 2014. The National Bureau of Statistics of China and China Energy Portal also confirms the decreasing coal share and reported that 68% and 68.5% of the grid electricity was produced using coal in 2020 [34,36]. To counterbalance the fossil fuel, the shares of hydro, wind and solar technologies showed an increasing trend.

For Germany and Norway, the Ecoinvent 3.7.1, 3.8 and 3.9 databases represent the year 2017, 2018 and 2019, respectively. The electricity mix of Germany showed a faster trend of decarbonization from the year 2017–2020 when compared to China. A reason for such higher shares of renewable can be the production disruption due to COVID-19 and therefore, factories did not consume fossil fuel like business as usual [37]. However, this does not contradict the fact that decarbonization is eminent as also seen between the years 2017–2018. So, to conduct an LCA, it is important to select the most recent available electricity mix to gain more accuracy in GWP results.

The electricity mix development of Norway shows a decreasing trend in the share of hydroelectric technology and increase in wind energy. Between hydroelectricity and wind, wind is associated with lower GWP as seen in Fig. 1. But between the years 2018 and 2020, the share of

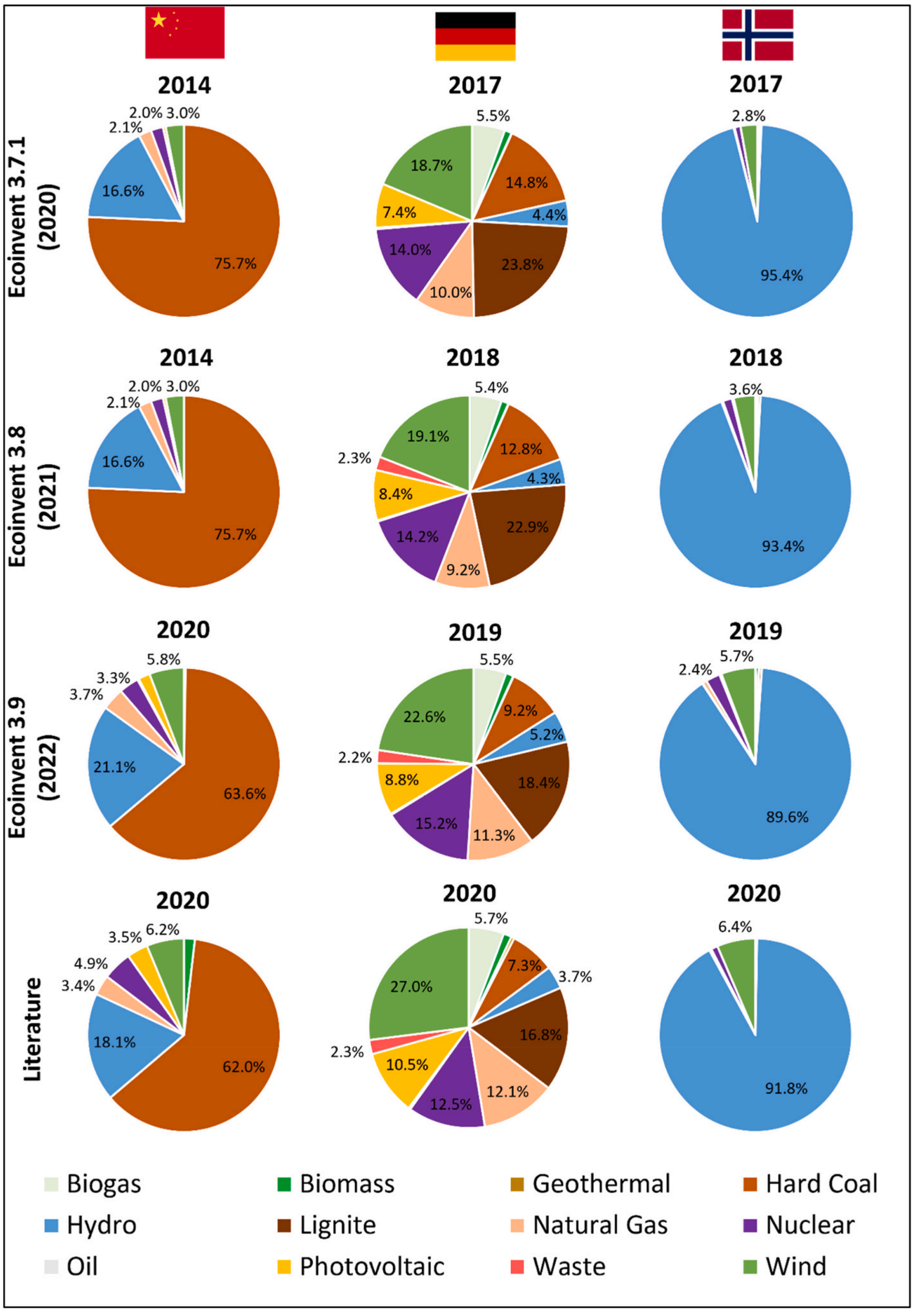

Fig. 5. Comparison of the share of different energy technology in the regional grid electricity (net electricity) of China, Germany and Norway. Data sourced from: Ecoinvent 3.7.1, 3.8 and 3.9 databases, and CEC Statistics (2021) for China 2020, Fraunhofer ISE (2021) for Germany 2020 and Statistics Norway, SSB (2022) for Norway 2020. The release year of the Ecoinvent databases are provided below for each database. The quantitative details of the values < 2% are not shown in the figure but listed in Table 4 in annex.

natural gas has increased which is associated with higher GWP. Henceforth, it can be said that the electricity mixes changes with location as well as over time. Fig. 6 shows the GWP resulting from the electricity mix as modelled in Ecoinvent 3.8 and the electricity mixes of the year 2020 as modelled in this work.

With regard to the location, the electricity mix of China has approximately twice the GWP when compared to its German counterpart due to higher share of coal. However, the electricity mix of Norway in Ecoinvent 3.8, mostly composed of renewables, showed approximately 20 and 40 times less GWP than its German and Chinese counterparts, respectively. Because of this significant difference, a PV system that is produced in Norway is also expected to have such lower GWP than a PV system produced in China. To focus on the key message, the electricity mixes from Ecoinvent 3.7.1 and 3.9 versions are not shown further. This is for the fact that 3.7.1 is outdated while 3.9 was unavailable at the time of study.

Furthermore, regarding the decarbonization of grids with time, the GWP of the Chinese electricity mix was 1049 g CO_2-eq./kWh in 2014 which decreased to 901 g CO_2-eq./kWh in the year 2020. In case of China, no significant disruption in energy production due to COVID-19 is observed from the historic trends till 2020. Similarly, due to increased shares of renewables, the electricity mix of Germany reduced the GWP from 532 to 418 g CO_2-eq./kWh between 2018 and 2020. However, as the share of renewables decreased in Norway with an increase in natural gas, the GWP also increased from 24 to 49 g CO_2-eq./kWh between 2018 and 2020. This provides clear evidence regarding how the shares of

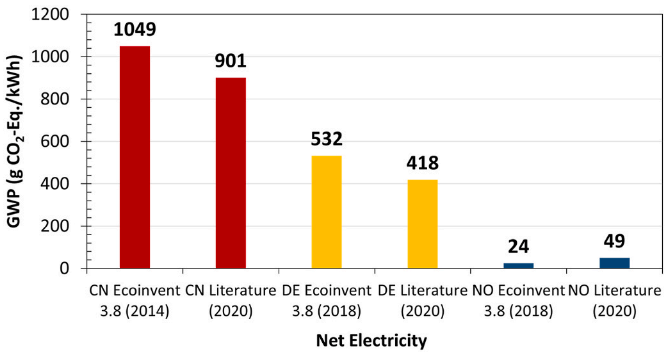

Fig. 6. Comparison of global warming potential (GWP in g CO_2-eq/kWh) of the electricity mix of China, Germany and Norway for Ecoinvent 3.8 year and 2020. Data sourced from China Electricity Council for China, Fraunhofer for Germany and Statistics Norway for Norway.

different technology can significantly impact the overall GWP of the electricity mix.

3.2. GWP of PV system production

The incorporation of the electricity mixes of China, Germany and Norway as foreground electricity in the LCA model shows that the selection of production location of the silicon to module PV value chain as well as for balance of system components has significant impact on the GWP of the PV system. The results of the GWP analysis of the PERC system for different locations, i.e., electricity mixes, are demonstrated in Fig. 7. Based on PEFCR, installation is assumed at an average European location where the average total electricity generation during 30 years of system operation is 29.25 MWh/kWp and the average global tilted irradiation (GTI) per module square meter is 1331 kWh/m^2.

With production in the Chinese grid the PV system inherits the highest GWP impact, 37.7 and 40.4 g CO_2-eq./kWh based on the years 2014 and 2020 respectively as the underlying electricity mix. The same PV system can be produced with approximately 40 % less GWP impact if produced at a German location. With higher share of renewables as shown for Norway, the GWP can be further reduced to 15.6–15.9 g CO_2-eq./kWh, which is approximately 60 % times lower than that produced in China. For this reason, when conducting an LCA, the application of an updated electricity mix during the calculation of the GWP is important although recent data is hard to find. For most regions, the electricity mixes are still progressing towards a share of technologies that is more climate neutral. Therefore, there is an opportunity to present GWP of the PV system by using the electricity mix of most recent years. However, in some regions, as shown in Fig. 6 for Norway, an updated year can also result in higher GWP. This is due to increase of non-renewables or renewables with higher GWP in the electricity mix to meet an increasing energy demand.

Analysing the life cycle phases of the PV value chain, it is observed that the GWP of the complete wafer production can be lowered from 11.4 to 2 g CO_2 -eq./kWh by changing the production location to Norway: reducing by a staggering 85%. The wafer production (and especially MG-Si, Poly-Si production and Cz Crystallization therein) is the most electricity intensive value chain part for the PV module production. The GWP emitted from most other life cycle phases of the three PV production is the same for background modelling since the underlying background modelling data in Ecoinvent is the same. Only the GWP for the aluminium frame production and BoS is higher for China. The reason is that the aluminium ingots required for frame and BoS, produced in China, are associated with more GWP than the ones produced in the European region and Ecoinvent provides data sets for aluminium ingot production in both regions. The authors of this study chose not to replace the electricity used to produce aluminium ingots with the foreground electricity. This reason behind is that in Ecoinvent 3.8 the electricity used for the aluminium ingots is modelled with aluminium

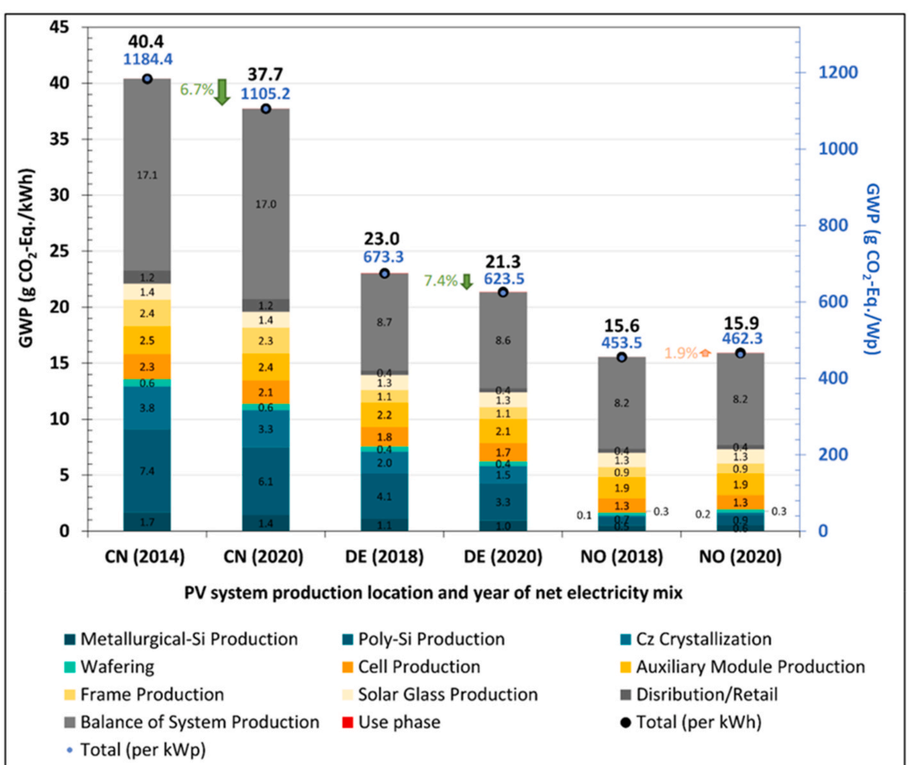

Fig. 7. Life cycle phase wise global warming potential (GWP) of the PV system using the electricity mixes of China, Germany and Norway for the Ecoinvent 3.8 year and 2020 as the foreground electricity. Blue represents GWP (g CO_2-Eq.) per W_p. Based on PEFCR conditions, average total electricity generation during 30 years of system operation is 29.25 MWh/kWp and the average global tilted irradiation (GTI) per module square meter is 1331 kWh/m^2.

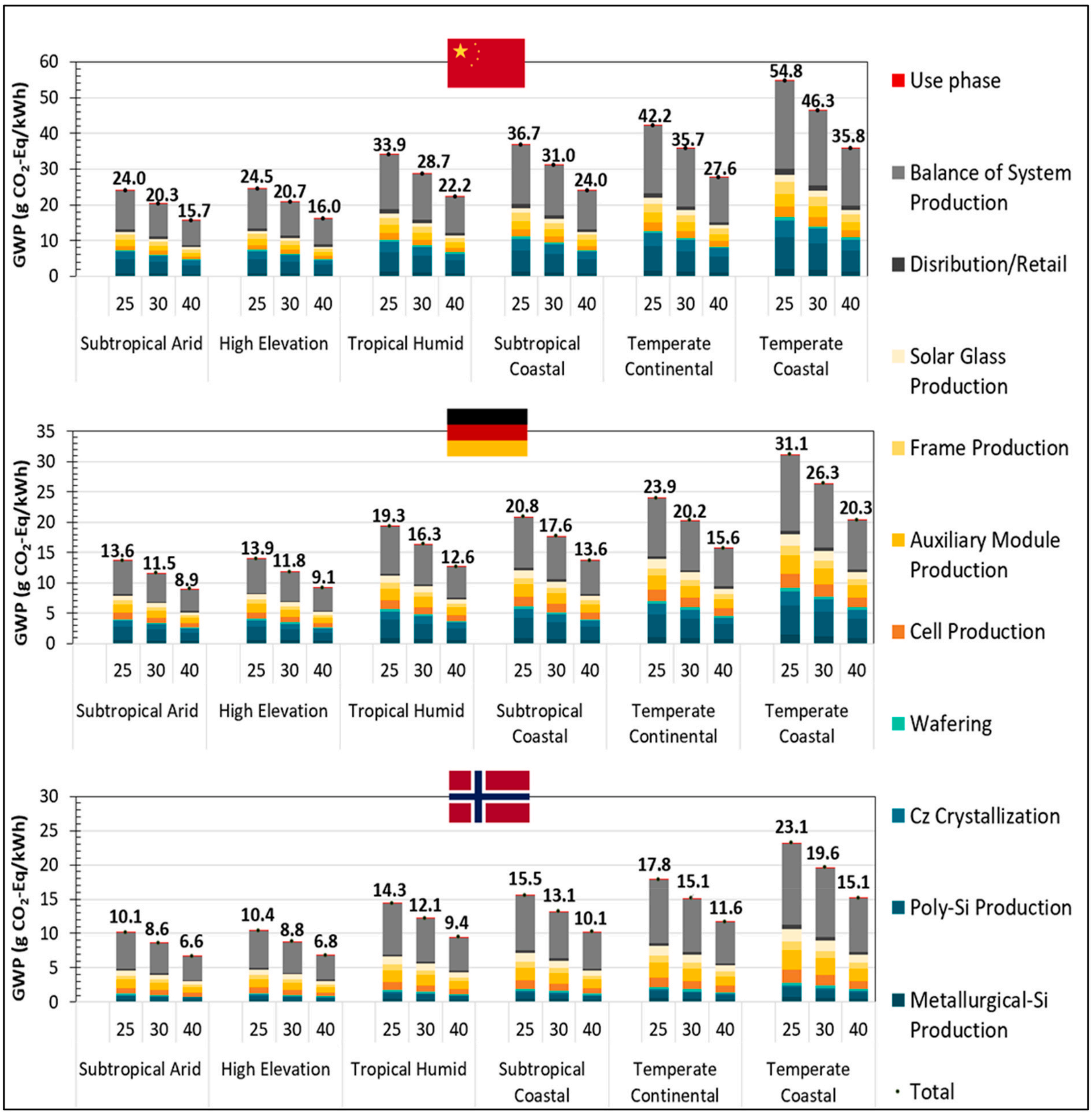

Fig. 8. Sensitivity analysis of GWP of the PERC PV system produced in three locations China, Germany and Norway to global in-plane irradiation (kWh/m^{2}a) of the installation location and lifetime (years). Electricity mix used for production reflects the year 2020.

industry specific datasets. The meta-information of the activity 'aluminium ingot, primary, to aluminium, cast alloy market' states that primary aluminium production is very energy intensive, and hence the location of production plants is often determined by access to large amounts of cheap electricity, which often results in an electricity mix that is different from the general grid mix of the countries where the production plants are located. Moreover, the ingot is processed to cast alloy (here modelled as background process) and later processed into the specific alloy (here modelled as foreground process) used for frame and BoS of the PERC PV module. Therefore, although associated with high GWP impact, this activity is considered a background electricity process within the PV value chain. However, it is recommended to further monitor the improvements in the aluminium specific electricity mixes and its impact on the GWP of the PV. Further details regarding the impacts of other life cycle phases of the PERC PV are explained in the study conducted by Müller et al. [9].

To conveniently assess the change in GWP of the PV production for different electricity mixes, this work also provides a "PV production GWP calculator". In short, with this calculator, GWP impact of the used foreground electricity for the PV system production can recalculated for different electricity mixes in each PV value chain step. The core aim of the GWP calculator is to quantify the change of GWP impacts due to the electricity mix of the supply chain location and thus, support in decision making process of the supply chain location of different production phases based on an environmental perspective. For example, based on this calculator, the GWP of a PERC system of which the wafer is produced in Norway, the cell and module production in Germany and the BoS (European location) components are produced completely of hydroelectricity can be estimated by using the tool to be 16.7 g CO_2-eq/kWh in PEFCR conditions. With the "PV production GWP calculator", the GWP reduction potential for each life cycle phase of the PV production value chain can be easily assessed for different combination of production location.

3.3. GWP sensitivity to installation location and system lifetime

For the downstream section, the PERC PV system is analysed for 6 different installation locations and the results are summarized in Fig. 8.

It is evident that, with respect to incorporation of temperature related losses, the energy yield generally increases with an increase of the global in-plane irradiation (kWh/m^2a) at the installation location. For a central European installation location with the temperate continental climatic conditions with global in-plane irradiation of 1266 kWh/m^2a, the GWP of the PV system produced in China, Germany and Norway resulted in 42.2, 23.9 and 17.8 g CO_2-eq/kWh respectively. Hence, at a subtropical arid installation location with a global in-plane irradiation of 2295 kWh/m^2a, the GWP of a PV system with 25-year lifetime and produced in China, Germany and Norway shows to be as low as 24.0, 13.6 and 10.1 g CO_2-eq/kWh respectively.

At the temperate coastal location, the global in-plane irradiation is lowest, at 972.9 kWh/m^2, and therefore, resulting in the highest GWP 54.8, 31.1 and 23.1 g CO_2-eq/kWh for the same three locations respectively. But even the highest GWP value of this assessment is showing lower results as the GWP for photovoltaics in the latest Ecoinvent 3.9 database, due to outdated datasets for PV therein.

Existing studies exhibit a wide range of carbon footprint for the PV modules as a complex interplay of factors (technical specifications, system boundary, background database, impact assessment method and software among others) influence the results. However, the key message is clear and in line with findings of this analysis. In this regard, a recent study by Gan et al. showed that the current supply chain of Si PV in USA (~20% module efficiency, 0.7% annual degradation, 30 year lifetime) has a carbon footprint of 36 g CO_2-eq/kWh (cradle to grave, including BoS) as ~85% of production takes place in China and Asia–Pacific countries [38]. When produced using the grid electricity of U.S. along with improving module efficiency, the footprint is expected to reduce by 43% within 2030. Another older study which analysed the mono crystalline Si PV in 2012 also concluded that modules built in China and shipped to Thailand generate 150 g CO2-eq/kWh whereas modules produced in Thailand or Germany generate 60 g CO2-eq/kWh due to cleaner electricity grids (cradle to grave, including BoS) [39]. The carbon footprints reported in our analysis compared to the footprint presented by Kittner et al. is a testament to the rigorous decarbonization efforts by the global national grids. The benchmark (0.7% annual degradation, 30 years lifetime) provided by the IEA PVPS Task-12 in 2022 shows that the impacts generated from multi-crystalline Si (18.0% module efficiency) and mono crystalline Si (20.0% module efficiency) can be 42.9 and 44.0 g CO2-eq/kWh whereas CdTe PV (18.2% module efficiency) can be 25.5 g CO2-eq/kWh (cradle to grave, including BoS and EoL dismantling, recycling, waste management) [23]. The benchmarks were calculated using the electricity mix representative of 2016 and installed at an average European location similar to our analysis. Moreover, through the temporal and spatial lens, a comparative study by the *National Renewable Energy Laboratory* also showed that Si PV modules (21.13% module efficiency, no degradation, 25–30 years lifetime) produced in the year 2020 in EU, US, China, and India had an embodied carbon of 11, 15, 20 and 22 g CO_2-eq/kWh, respectively. This reduced to 7 g CO_2-eq/kWh for EU and 8 g CO_2-eq/kWh for the three others by the year 2050 (cradle to gate, average, US and southern European installation) [40]. In the same study, Wikoff et al. also compared the thin-film CdTe PV (19% module efficiency, no degradation, 30 years lifetime). Embodied carbon within the CdTe modules were 7, 8, 9 and 10 g CO_2-eq/kWh when produced at EU, US, China, and India respectively. This further reduced to a mere 5 g CO_2-eq/kWh by year 2050 due to temporal sensitivity. Apart from this, a CdTe module (18.7% module efficiency, 0.3% annual degradation, 30 years lifetime) showed 207 g CO_2-eq/Wp (cradle-to-grave) when produced in USA, compared to 231 g CO_2-eq/Wp when produced in India due to higher carbon footprint of the Indian grid [41]. On the contrary, Sinha et al. further showed that the American CdTe modules, when installed in USA, scored 12 g CO_2-eq/kWh (cradle-to-grave, no BoS), compared to 9 g CO_2-eq/kWh when produced and installed in India-an opposite picture due to higher irradiation at the Indian installation location.

Simultaneously, with the increase in the lifetime of a PV system the energy production of PV increases, and subsequently, the GWP per kWh of electricity decreases as seen in Fig. 8. Assuming a high elevation installation, with 30 years lifetime instead of 25 years, the GWP of the PV produced at the three examined locations reduces approximately by 15%. With a 40 years lifetime, as PV manufacturers already provides such a lifetime warranty [33], the GWP reduces by approximately 25% (to 25 years lifetime) leading to 15.7, 8.9, and even 6.6 g CO_2-eq/kWh for Chinese, German and Norwegian produced PERC PV system respectively. Therefore, for environmental reasons, efforts should be directed towards improving the lifetime of the PV module.

4. Conclusion

PV systems have great potential in tackling the climate change and energy crisis due to its low GWP impact and cost competitiveness for renewable energy production. As the finding of this analysis shows, depending on the electricity mix of the production location and its year of data collection, location of installation and lifetime of PV, the GWP of the same PV system configuration can range between 54.8 and 6.6 g CO_2-eq./kWh for a PV system production in China and Norway respectively, of alternating current (AC) electricity generated; a reduction by almost 88% depending on the location of the products' value chain. Approximately 58% reduction can be allocated only to used electricity mix in production because electricity used in the production of PV generates the highest share of impacts in the overall GWP. Calculated through the provided "PV GWP calculator", when 100% photovoltaics are used for the complete production of the PV system, the GWP could be 16.5 g CO_2-eq./kWh for PEFCR conditions. The GWP of PV calculated in this work shows, that PV can have significantly lower footprint than the

GWP of PV as currently available in the Ecoinvent 3.9 database with 90 g CO_2-eq./kWh. As a state-of-the-art GWP value for PV technology, which is independent from installation location, we propose to rather use our updated values for a PV system produced in China (where the dominating part of the PV production is located) under PEFCR installation conditions. In this work, the GWP for state-of-the-art silicon PV technology is calculated to be at 37 0.7 g CO_2-eq./kWh, using the 2020 Chinese electricity mix and based on PEFCR installation conditions. This is ~58% less as currently available as average GWP for PV.

Furthermore, this study also demonstrated the impacts of installation location and module lifetime on the GWP of the PERC system. For a PV system (with 25 year-lifetime) produced in Germany with an electricity mix reflecting the year 2020, the GWP is reduced from 21.4 g to 8.9 CO_2-eq./kWh through installing the system in a location of high irradiation and an increased lifetime of 40 years. In this case, approximately 58% GWP reduction potential is seen.

The foreground electricity in this study accounts for approximately 36%, 31% and 3% of the total GWP for CN, DE and NO production locations respectively. This means that there is a further opportunity to improve the GWP of system even beyond what is shown in this study, through changing the supply chain for the background materials as well.

This work also provides guidelines to model an updated electricity mix for the LCA practitioners which will support them in generating LCAs that reflect the current time. Even when using Ecoinvent electricity datasets, the authors caution against the use of low or medium voltage electricity alone and encourages the use of the net electricity model when representing the electricity grid of a country.

The upstream production location, downstream installation location and lifetime have high GWP reduction potential. Strategic planning of these phases will lower the GWP and open opportunities to create a more sustainable product.

CRediT authorship contribution statement

Abeer Ali Khan: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Christian Reichel:** Validation, Conceptualization. **Pamela Molina:** Writing – review & editing, Validation. **Lorenz Friedrich:** Validation, Conceptualization. **Dilara Maria Subasi:** Writing – review & editing, Validation. **Holger Neuhaus:** Writing – review & editing, Validation. **Sebastian Nold:** Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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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.2024.112724.

Annex.

Table 4
Breakdown of different energy generating technologies which composes the net electricity of China, Germany and Norway. For all three cases, data from four sources were observed namely Ecoinvent 3.7.1, Ecoinvent 3.8, Ecoinvent 3.9 and literature data as listed in Table 1.

Energy Generating Technology	CN Net Electricity Share				DE Net Electricity Share				NO Net Electricity Share			
	Ecoinvent 3.7.1 (2014)	Ecoinvent 3.8 (2014)	Ecoinvent 3.9 (2020)	Literature (2020)	Ecoinvent 3.7.1 (2017)	Ecoinvent 3.8 (2018)	Ecoinvent 3.9 (2019)	Literature (2020)	Ecoinvent 3.7.1 (2017)	Ecoinvent 3.8 (2018)	Ecoinvent 3.9 (2019)	Literature (2020)
Biogas	0.0%	0.0%	0.0%	0.0%	5.5%	5.4%	5.5%	5.7%	0.0%	0.0%	0.1%	0.0%
Biomass	0.0%	0.0%	0.0%	1.8%	1.2%	1.2%	1.2%	1.3%	0.2%	0.3%	0.5%	0.0%
Blast Furnace Gas	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
Coal Gas	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Geothermal	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%
Hard Coal	75.7%	75.7%	63.6%	62.0%	14.8%	12.8%	9.2%	7.3%	0.3%	0.4%	0.4%	0.2%
Hydro	16.6%	16.6%	21.1%	18.1%	4.4%	4.3%	5.2%	3.7%	95.4%	93.4%	89.6%	91.8%
Lignite	0.0%	0.0%	0.0%	0.0%	23.8%	22.9%	18.4%	16.8%	0.0%	0.1%	0.1%	0.1%
Natural Gas	2.1%	2.1%	3.7%	3.4%	10.0%	9.2%	11.3%	12.1%	0.1%	0.2%	0.7%	0.3%
Nuclear	2.0%	2.0%	3.3%	4.9%	14.0%	14.2%	15.2%	12.5%	1.0%	1.5%	2.4%	1.1%
Oil	0.0%	0.0%	0.3%	0.0%	0.2%	0.2%	0.2%	0.3%	0.0%	0.0%	0.0%	0.0%
Peat	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Photovoltaic	0.4%	0.4%	1.9%	3.5%	7.4%	8.4%	8.8%	10.5%	0.0%	0.0%	0.0%	0.0%
Solar Thermal	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Waste		0.0%	0.0%	0.0%	0.0%	2.3%	2.2%	2.3%	0.0%	0.3%	0.3%	0.0%
Wind	3.0%	3.0%	5.8%	6.2%	18.7%	19.1%	22.6%	27.0%	2.8%	3.6%	5.7%	6.4%
Sum of Shares	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

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