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Role of solar PV in net-zero growth: An analysis of international manufacturers and policies

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Abstract

In May 2022, the European Commission adopted a new European Union (EU) Solar Energy Strategy [1] aiming to ensure that solar energy achieves its full potential in helping to meet the European Green Deal's climate and energy targets. A goal of the strategy is to reach nearly 600 GW of installed solar photovoltaics (PV) capacity by 2030. While Europe is a pioneer in the definition of new policy requirements to ensure the circularity and sustainability of PV products, its manufacturing capabilities are limited. The EU mostly imports PV modules from China, which for the last decade has remained the global leader in PV manufacturing across the supply chain. This article aims to provide insight into the solar PV industry and the surrounding policy context, focusing on the manufacturing phase and its climate impact. It provides a comparative overview of the key players in the European and Chinese PV markets with an overview of the whole supply chain (i.e. production of polysilicon, cells, wafers and modules). Having in mind the net-zero commitments across the globe, and a central role of the solar PV in the energy transition, the demand for PV products is expected to grow exponentially in the next decades. With this in mind, the authors look into environmental impacts from the PV manufacturing. A simplified analysis concludes on the suitability of the PV manufacturing process today and indicates the opportunities for the net-zero transition in the future. While the focus is on the carbon impacts of the solar PV industry, the authors also identify other relevant aspects (such as circularity), laying the ground for a future research.

KEYWORDS
carbon neutrality, net-zero industry, photovoltaics

1 | INTRODUCTION

Solar photovoltaic (PV) has become a relatively affordable technology and is being deployed rapidly as a pillar of the clean energy transition worldwide. Among many of the projections available, the net-zero scenario (NZE)[*] of the International Energy Agency (IEA) is the reference for this article; it is the only IEA scenario that is in line with the target to limit the global temperature by 1.5°C by 2050. According to the IEA NZE scenario, the share of wind and solar electricity generation will increase globally from 10% in 2021 to 40% in 2030, reaching nearly 70% in 2050 [1]. This will result in around a fivefold increase in solar PV capacity over the next decade (from 1 TW in 2022 [2] up to 5042 GW in 2030), leading to significant growth in demand for PV modules.

The installation of PV systems is expected to play a key role in meeting climate targets. Compared with other electricity sources, solar PV has one of the lowest life-cycle GHG emission levels per kilowatt hour generated. Nevertheless, PV presents great variability in terms of its carbon intensity in the manufacturing process, with some modules almost doubling the average. To that extent, when pursuing the full potential of this technology, it is important to consider that in 2021, 52 million tonnes of CO_2—or 0.15% of all global energy-related emissions—stemmed from worldwide PV module manufacturing. These emissions are expected to rise sharply in the short term, due to the ambitious net-zero carbon pledges worldwide [1, 3].

The carbon footprint (CF) of PV systems is largely determined in the design stage, with the manufacturer's choice and quantity of materials and components playing an important role.[†] Furthermore, it is significantly influenced by the source of electricity in the production process (see Figure 1). Today, coal generates over 60% of the electricity used in solar PV manufacturing globally [4]. Therefore, the use of low-carbon electricity in the manufacturing process could reduce emissions significantly, by up to 50% [5].

In this context, the European Union (EU) and China play a key role, being two important PV value chain players committed to reaching carbon neutrality by 2050 [6] and 2060 [7], respectively. China is a global leader in PV manufacturing, with production concentrated mainly in the provinces of Xinjiang and Jiangsu, where coal accounts for more than 75% of the annual power supply [1]. The EU, on the other hand, is a front runner when it comes to the regulatory side, a pioneer in the definition of new policy requirements to ensure the circularity and sustainability of PV products (i.e. Ecodesign requirements focusing on material efficiency and CF) [8, 9]. Bearing in mind that the EU mostly imports PV modules from China, the two countries are interdependent [10, 11]. In fact, the Chinese and European PV policy and industry contexts and the interrelation between them have been receiving increasing attention in both the scientific literature and policy discussions [12–14]. However, the sustainability aspects and implications of this interdependent relation have not yet been studied sufficiently in depth, leaving an important knowledge gap to address.

Against this backdrop, the main objective of this study is to provide insight into the European and Chinese PV industry and policy contexts in combination, with a focus on sustainability, in particular the manufacturing phase and its climate impact. To this end, we employ a comparative analysis method [15]. This approach has already been used to compare industry and policy contexts in relation to renewable energy technologies. For example, Bergek and Jacobsson [16] used it to compare the German, Dutch and Swedish wind turbine industry, while Yu et al [12] compared the PV industry and policies in Germany, Japan and China in the context of globalisation dynamics. In this study, we apply the comparative analysis method to provide an overview of the key players in the European and Chinese PV markets along the whole supply chain (i.e. production of polysilicon, cells, wafers and modules). In addition, we pinpoint key pledges and legislation, recently passed and under preparation, to catalyse the transition to carbon-neutral PV manufacturing on both sides. The main contribution of the study consists of considering these insights together, reflecting on their sustainability implications, mainly in terms of manufacturing and emissions, while also arguing for the need for future research on the social and circularity aspects.

The remainder of the article is structured as follows. In Section 2, based on systematics desk research, we sketch the policy context for the net-zero transition in the solar PV sector in the EU and in China. In Section 3, we turn to the industry context in both areas. In Section 4, we focus on the environmental impacts of PV manufacturing. Finally, we close with Section 5 discussing the relevance of the study for policymaking and business practice, before identifying potential directions for future research.

2 | POLICY CONTEXTS FOR THE NET-ZERO TRANSITION IN THE SOLAR PV SECTOR

To date, 93 countries [17], responsible for nearly 80% of the global greenhouse gas (GHG) emissions, have committed to net-zero growth. With the binding commitment of a 55% emission reduction by 2030 [18], Europe aims to reach carbon neutrality by 2050.[‡] China, on the other hand, aims for CO_2 emissions to peak before 2030 and to achieve carbon neutrality before 2060 [19].

2.1 | Towards carbon neutrality by mid-century: Europe's perspective

The EU is committed to making a path to a green transition and becoming the first continent to reach climate neutrality by 2050

[*]When compared to other existing scenarios for the energy transition, there are others with more ambitious projections regarding the share of solar PV in the energy system; see figure 2.11, p. 63 in the IEA, sector [93]. While under the IEA NZE scenario the annual capacity installed is expected to reach 600 GW between 2030–2050, in the most ambitious scenario by Heagel et al [73], it is up to 2.4 TW in 2035.

[†]The type of materials used for PV modules as well as the processing technology employed are important determinants of the environmental impacts of the production stage. For example, thin-film PV technologies (CdTe) intrinsically require less energy for their production than traditional silicon-based modules, up to 50% less per watt-peak of capacity. Polysilicon production is the most CO_2-intense segment of the manufacturing [47].

[‡]A few individual Member States set the goal to reach carbon normality by 2030 (Finland) and 2045 (Germany and Sweden).

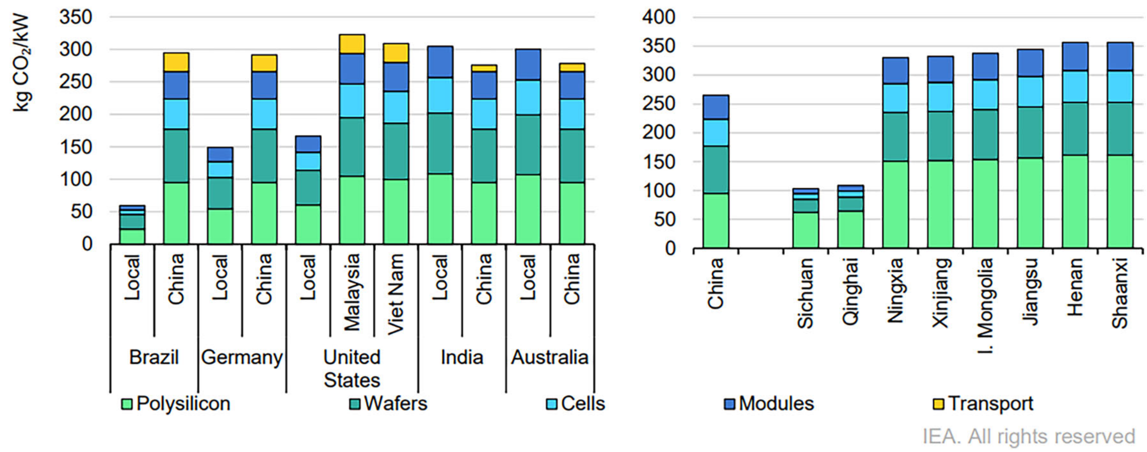

FIGURE 1 Hypothetical solar PV manufacturing emissions intensities for selected countries (kg CO_2/kW) [4].

under the European Green Deal [20]. To deliver on the objectives of the Green Deal, the European Commission adopted the Fit for 55 package on July 2021 [18]: This legislative initiative is set to raise the climate ambition and reduce GHG emissions by at least 55% by 2030, compared to 1990 levels.

The EU recognises the central role of solar PV energy in paving the way to carbon neutrality and reducing dependence on fossil fuel imports. In May 2022, in response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine, the European Commission adopted the REPowerEU Plan [21], which included the EU Solar Energy Strategy [22] that outlines initiatives to accelerate the deployment of solar technologies and sets the goal of reaching 320 GW[§] of PV solar capacities by 2025, with a further increase up to nearly 592 GW by 2030 (compared to 136 GW in 2020). The rapid growth of demand following the implementation of the EU Solar Strategy will need to be met to some extent by imported products (according to expert estimates, it will be at least 50% of demand by 2030[¶]). Aiming to create a supportive framework for scaling up the EU's manufacturing capacity for net-zero technologies, such as PV, the European Commission announced the Green Deal Industrial Plan [23].[#] Its integral part is the Net-Zero Industry Act (NZIA), which proposes a framework to enable conditions for setting up net-zero technology manufacturing in Europe and sets the objective of reaching an overall annual EU manufacturing capacity benchmark of at least 40% of annual deployment needs by 2030. The overall headline benchmark considers the need for scaling up manufacturing capacity not only for end-products (PV modules) but also for specific components, for instance, wafers, ingots, solar cells, glass and others.

The EU is a front runner in laying the ground for the sustainability requirements for PV products. For instance, the Netherlands has introduced environmental product declaration (EPD) requirements for PV modules, which include CF reporting. France has a mandatory requirement for a CF declaration in public tenders and grants bonus points for a low CF [11]. Spain, meanwhile, includes criteria on the declaration of the CF in public auctions for solar PV installations [24].

To ensure that the PV modules and inverters deployed in the EU are environmentally sustainable, the European Commission is currently working on regulatory measures [4] in the framework of the Ecodesign Directive [25] and the Energy Labelling Regulation [26] for the PV products (modules and inverters) that enter the EU single market, regardless of where they were produced. The objectives of these measures include:

- increasing performance and durability of PV products, inter alia, by increasing the quality of manufacturing processes and facilitating their repair;
- increasing PV products' circularity on the EU market by increasing recyclability at the end of life;
- shifting the EU market towards PV products with lower impacts, in terms of GHG emissions, from the production stage and incentivising further development of such products; and
- empowering consumers to make an informed and sustainable choice at the point of sale.

The measures would concern the efficiency, durability, reparability and recyclability of PV products. Requirements on the quality of the manufacturing process and the CF of PV modules are also being considered, as they could foster (as shown more in detail in the

[§]The PV capacities are expressed in alternating current (AC) to allow for a better comparison with other power generation plants. PV manufacturing capacities are expressed in the direct current (DC) values, with the conversion unit of DC/AC = 1.25.

[¶]The European Commission presented in October 2022 the European Solar PV Industry Alliance with an objective of reaching 30 GW of European manufacturing capacity by 2025, across the entire value chain. Following the expert estimates by 2030, it is feasible that around 35 GW of PV manufacturing in Europe would respond to around 48% of demand based on the EU Solar Strategy.

[#]In this regard, the European Industrial Strategy [10], which seeks to make the EU industry more competitive globally and enhance Europe's strategic autonomy, highlights the importance of regaining and strengthening the EU's competitive edge in the solar photovoltaic industry and the battery sector.

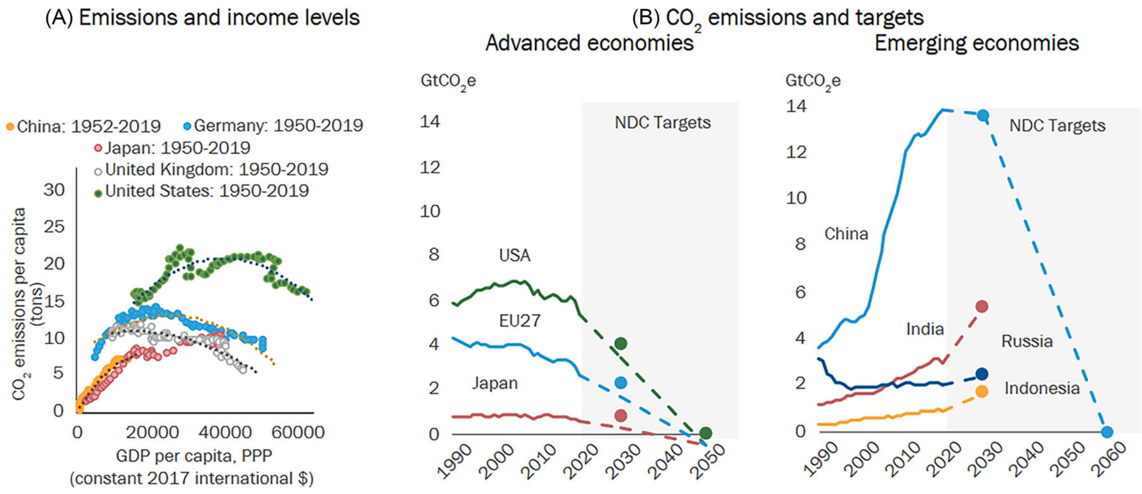

FIGURE 2 Nationally determined targets for carbon emissions set by major economies [27].

remainder of this paper) innovation in the design and manufacturing stage as well as the use of renewable energy for their production.

2.2 | 2030 emission peak and carbon neutrality by 2060: China's perspective

China is the world's largest CO_2 emitter, responsible for a third of the world's emissions [27]. In 2015, it was a co-signatory of the Paris Agreement and thus became one of the key actors committed to mitigating global climate change. China started to set tangible targets to reduce CO_2 emissions with initiatives such as the National Emission Trading Scheme (ETS), operationalised in 2021, which covered 40% of Chinese emissions and is the largest of this kind in the world [28]. At the same time, in the 2020 UN General Assembly, China committed to reaching the peak of its CO_2 emissions before 2030 and achieving carbon neutrality before 2060 [7, 29]. China's carbon reduction targets are ambitious considering that China's income level is considerably lower and the pace of decarbonisation is faster than other major economies that committed to similar targets [27] (see Figure 2).

The 2020 14th 5-year Plan was the most important policy document setting the overall strategy for Chinese development in the years 2021–2025 [29]. Apart from putting into law the earlier 2020 commitments to carbon neutrality by 2060, it also introduced the industrial strategy with an eye on 2035 to support meeting these targets. For instance, it included a detailed plan for China's energy mix diversification by mapping out the planned investments in new energy technologies and construction of major clean energy bases. In provinces that are key to PV manufacturing, Xinjiang and Jiangsu, the plan promises to create renewable power bases of solar, hydro, wind and thermal energy mixes for Xinjiang and thermal paired with hydropower for Jiangsu. These initiatives are planned to increase the percentage of renewables in the country's overall energy mix to 20% by 2025 (compared to 15.3% in 2019 [30]).

In two 2021 documents entitled 'China's Achievements, New Goals and New Measures for Nationally Determined Contributions' and 'China's Mid-Century Long-Term Low Greenhouse Gas Emissions Development Strategy', China further committed to increase the share of non-fossil fuels in primary energy consumption to around 25% and total installed capacity of wind and solar power to over 1.2 TW by 2030 [30].

China has introduced specific policies supporting investments in renewable technologies (and the PV sector specifically) since as early as the 1990s, with a steep increase in the 2000s [31]. As for recent developments, in 2015, China released a strategy called the 13th Solar Energy Development 5-Year Plan (comparable to the EU Solar Strategy), which set targets of 105 GW of solar energy to be achieved by 2020 and a 50% cost reduction in comparison to 2015 [32]. Additionally, the Chinese Ministry of Finance issued many smaller regulations aimed mainly at providing direct support to the PV industry (i.e. the 2020 'Subsidies for Renewables' set a centrally managed renewables subsidy budget of USD 13.04 billion, representing a 7.5% year-on-year increase). Several such policies in recent years, that is, 2020 Several Remarks on Promoting the Healthy Development of Non-water Renewable Energy Generation, 2021 Notice on Matters Concerning the New Energy Feed-in Tariff Policy or the 2023 Renewable Energy Electricity Subsidy, put local authorities in charge of distributing funding to renewable energy companies.** Moreover, the 2020 Notice on Matters Concerning the Development and Construction of Wind Power and Photovoltaic Power Generation introduced interprovincial competition between provincial energy authorities for centrally allocated funds to support PV-related projects.

As to the specific policies targeting circularity in the PV sector, these are only emerging currently, with the notable examples of

**In using the name 'subsidy' in the title of the legislative initiatives listed here, we followed the International Energy Agency's translation, which can be found here: https://www.iea.org/policies?country=People%27s%20Republic%20of%20China&topic=Renewable%20Energy. The original Chinese names of these acts tend to use word '资金', which can also be translated as 'fund'.

industry standards, such as the 2021 'General technical requirements of thin-film photovoltaic module recycling and reusing for use in building' and 'Photovoltaic module recycling and reutilization general technical requirements' issued by the State administration, as well as 2022 'General technical Requirements for crystalline silicon PV module recycling and recovery' introduced by China Photovoltaic Industry Association. The most important piece of legislation in this regard is the 2023 National Development and Reform Commission (NDRC)-released 'Guiding opinions on promoting the recycling of retired wind and photovoltaic equipment' regulation, which is a wide-lens policy encouraging the creation of a comprehensive recycling system and the incorporation of the recycling considerations into the entire life cycle of the product. While as with most of the PV policies, it is mainly concerned with technological advancement of the sector, it also introduces elements that are akin to the EU-type Ecolabel requirements by encouraging green design (the incorporation of the easy recycling and dismantling considerations at the design stage of the product) [33].

Two trends can be noted in those sector-specific policies. One is the utilisation of instruments, such as direct funds for home companies, local content requirements or import tariffs. The other is the overall tendency towards decentralisation of supervision and financing of the initiatives in this space. At an early stage of establishing policies on renewable energy sources, much of the planning and funding was distributed centrally. However, the current trend indicates increasing devolution of target-setting, project planning and financing of industry-wide and household use of PV systems and related power grids to provincial authorities. This devolution follows the familiar pattern of interprovincial competition for central resources to develop new projects, typical of how economic development was encouraged throughout the entire period of market reforms in China. This changing dynamic requires that China's decarbonisation be approached from province-level data to fully understand its impact on the manufacturing of PV in China. The role of provinces is crucial for decarbonisation, as these are the main actors who 'turn general statements from the leadership into action' [34]. It is also important to consider data on the provincial level, as China's carbon emission patterns are heavily skewed towards northern provinces, where most of the solar and wind power is also produced [35]. As of 2021, four provinces in China's North—Ningxia, Inner Mongolia, Xinjiang and Shanxi—are the most carbon-intensive [36]. As most PV module manufacturing is concentrated in Xinjiang and Jiangsu, their decarbonisation pledges are particularly important. In their 13th 5-year provincial plans (FYPs), these two provinces set their decarbonisation targets at 20.5% for Jiangsu and 12% for Xinjiang [30]. These pledges are now topped in the 14th FYP, with Xinjiang, the more carbon intensive of the two, committing to achieving an 18% share of non-fossil energy in primary energy consumption by 2025 [37].

3 | INDUSTRY CONTEXT FOR THE NET-ZERO TRANSITION IN THE SOLAR PV SECTOR

3.1 | Key players in the global PV market

The exponential increase in solar PV deployment worldwide translated into an increased demand for PV module production. During the last decade, PV capacity manufacturing not only has experienced a sharp increase [38] but also has moved from Europe, Japan and the United State to China, which has secured its leading position as a manufacturer of PV and dominates every single solar PV supply chain segment (the country's share in all manufacturing stages exceeds 80%) (Figure 3).

China will most certainly remain the leading PV producer, increasing its production capacity. In 2022, global solar PV manufacturing capacity increased by over 70% to reach almost 450 GW, with China accounting for over 95% of new facilities throughout the supply chain. The latest IEA data indicate that current (2024) module manufacturing capacity in China exceeds 800 GW [39]. The Chinese PV industry is leading not only in the size of its production but also in technological

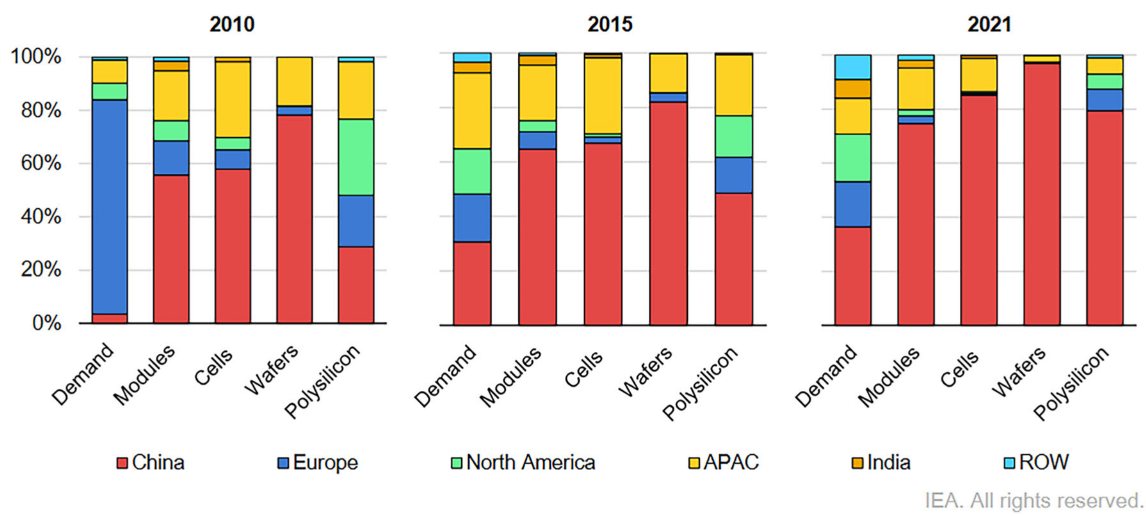

FIGURE 3 Solar PV manufacturing capacities by country and region [4]. APAC, Asia-Pacific region excluding India; ROW, rest of the world.

innovation and record-breaking efficiency [40]. Currently, the tendency is to produce high-power, large-format modules, with 210-mm-type cells produced with n-type technology already being mainstreamed [41]. This transformation was possible thanks to the low labour and energy costs, paired with the government policy of subsidising and protecting own industry, including business strategies of entering into partnerships with overseas companies through joint ventures [42]. For the last decade, several Chinese PV module manufacturing companies were already the largest in the world by both market share and volume of modules shipped (see Tables 1 and 2).

Regarding the EU, at the end of 2022, there were 157 companies in Europe with a total production capacity of 9.2 GW for modules and 69.9 GW for inverters, yet not fully utilised [43]. To support the objective of the NZIA, the Commission presented in October 2022 the European Solar PV Industry Alliance [44] with an objective of reaching 30 GW of European manufacturing capacity by 2025, across the entire value chain.

TABLE 1 Exemplary initiatives of the PV module manufacturing in the EU and China.

	Europe	China
Local manufacturing (i.e. PV modules)	Europe has a marginal role in PV module production worldwide. There were 157 companies in Europe with a total production capacity of 9.2 GW for modules [43] The German chemical group Wacker Chemie is the fourth largest producer (20 GW) of solar polysilicon worldwide	Currently, 80% of PV modules globally are produced in China [45] Some of the globally leading companies in the sector are based in China, including Longi Green Energy Technology Co (隆基), Jinko Solar (晶科能源), Trina Solar (天合光能), JA Solar Holdings (晶澳太阳能), Yingli Solar (英利太阳能), Suntech Power Holdings Co Ltd (尚德太阳能), Risen Energy (东方日升) and Astronergy (正泰新能), among others
Production (incl. import and export)	On average, Europe imports 80% of all the PV modules installed, 89% of which from China [46]	In 2021, on average, 40% of PV cells and modules production was exported to the EU [47]
Expansion plans	Several European companies announced their intention to increase their production capacities. Below are a few exemplary initiatives: ENEL will increase its current 200 MW production of heterojunction modules to 3 GW **(F)**. Meyer Burger in Freiberg and Thalheim plan to expand the capacity of 1.4 GW of heterojunction cells and 1 GW of heterojunction modules, respectively, by the end of 2022 **(F)** Greenland (a Spanish start-up) in collaboration with Fraunhofer Institute (ISE) and Bosch announced the construction of a 5 GW production plant for monocrystalline silicon wafers for PERC cells in Seville **(A)** CARBON's first gigafactory is planned to be located in the Marseille Fos seaport and will have an annual production capacity of 5 GW of cells and 3.5 GW of modules, approximately 12 million units. It will cover approximately 60 ha of industrial facilities. Its budget will amount to EUR 1.5 billion and it will employ more than 3000 people in 2025 and 10 000 people in 2030 [48] **(A)** The 3Sun factory in Catania, Italy, which currently has a production capacity of around 200 MW per year, plans to expand its production of photovoltaic panels to achieve 3 GW by July 2024 [49] **(F)** MCPV is planning to build 3 GW solar cell and module factory in the Netherlands, with an initial capacity of 300 MW and an expected increase to 3 GW by 2026 [50] **(A)** Three German solar PV companies, namely, Wattkraft Systems, PV module manufacturer Heckert Solar and solar glass supplier Interfloat Corporation, launched an expression of interest to add 10 GW of solar manufacturing. The first part of the project will be the expansion of module production in Langenwetzendorf, Thuringia, to reach an annual capacity of 2.8 GW. In Frankfurt, existing facilities will be modified to produce solar cells, polysilicon and wafers each with a 5 GW of annual capacity, while in Brandenburg a solar glass manufacturing plant will be built [51] **(A)**	Exemplary initiatives of some of the top Chinese PV companies in recent years are as follows: Longi Green Energy announced a capacity expansion for 100 GW wafers and 50 GW cells [52] and a new 10 GW module factory [53] **(F)** In 2022, Trina Solar unveiled new expansion plans, with 10 GW of wafer capacity and 300 000 units of industrial silicon by 2025. Additionally, the annual targets have been set to manufacture 35 GW of monocrystalline silicon, 150 000 t of high-purity polysilicon, a 10 GW cell and 1 GW module in a new PV base in Xining city, Qinghai provinces, which is currently under construction (will be finished in 2025) [54] **(A)** Jinko Solar has announced expansion plans in 2023, with the opening of a new panel-manufacturing factory (based in Haining, Zhejiang province). The factory will produce 11 GW of high-efficiency solar cells and 15 GW modules **(A)**, which adds to its other recent investments in 2022, which added an 11 GW high-efficiency solar cell facility, 24 GW high-efficiency modules, 16 GW module production lines and a 20 GW wafer manufacturing facility **(F)**. This comes on the top of its already achieved (in 2022) overall 65 GW capacity in the production of monowafers, 55 GW in solar cells and 70 GW in solar modules [55] JA Solar announced expansion plans in 2022 with several new factories. In Shijiazhuang (Hebei province), the company has built a 10 GW wafer slicing factory and a 10 GW solar cell production factory [56] **(F)**. In Dongtai (Jiangsu province), it will set up a 10 GW solar cell factory and a 10 GW module factory, both to be completed before the end of 2024 [57] **(F)**

Abbreviations: **(A)**, announcement; **(F)**, founded initiative; **(A)**.

TABLE 2 Voluntary initiatives by industry (examples).

	Europe	China
Voluntary initiatives by industry	The German chemical group Wacker Chemie, the fourth largest producer of solar polysilicon worldwide [61], has joined Race to Zero, the United Nation's carbon neutrality initiative. The company is committed to achieving net-zero GHG emissions by 2045 and has set mid-term goals for 2030, reducing absolute scope 1 and 2 GHG emissions by 50% and scope 3 by 25% compared to 2020 [62] Also, Enel Green Power, who has developed the 3Sun Gigafactory, set to become the largest factory producing bifacial PV modules in Europe, has pledged to achieve full decarbonisation by 2050. In the medium term, the Italian multinational commits to reducing scope 1 GHG emissions by 80% per kWh by 2030 compared to 2017, limiting them to 82 g CO_2/kWheq [63]	Longi—the world's largest producer of monocrystalline silicon wafers in 2021 with a market share of 22.1% in PV crystalline modules and production of 45–47 GW of modules shipped in 2022 [41, 64]—has pledged to use 70% renewable energy by 2027 and 100% by 2028 Trina Solar, also one of the top global companies with a market share of 9.42% in PV crystalline modules in 2021 and 43 GW of modules shipped in 2022 [44], is transitioning some of its production facilities to meet the net-zero standards. In 2022, Trina Solar's manufacturing process of 210 mm Vertex modules was recognised as industry-leading in terms of low carbon emissions. In 2023, Trina's Yiwu, Zhejiang province-based factory was the first PV-producing factory to be awarded Zero Carbon Factory status [65] Jinko Solar, with a market share of 4.9% in PV crystalline modules in 2021 [64] and 42–43 GW of modules shipped in 2022, pledges to use 100% renewable energy by 2025 JA Solar Holdings had a market share of 15.27% in PV crystalline modules in 2021 and 39.75 GW of modules shipped in 2022 [44]. The company's 2022 report indicated a 33% reduction in GHG emissions intensity for that year. The company has also pledged its commitment to greening its supply chains, with its six bases already being included on the 'Green Factory' list by the Ministry of Industry and Information Technology, and its products obtained carbon footprint certification from Certisolis in France as well as environmental product declaration certification from ULEPD in Italy. Additionally, the company opened a PV recycling initiative with PV CYCLE to promote dismantling and recycling of end-of-life products [66]

3.2 | Industry commitments and pledges

The urgency of climate mitigation action provide a stimulus for the PV industry and a unique opportunity to re-emerge more competitively in the coming years. The discussion on reducing emissions from PV product manufacturing is not new. In fact, the solar industry has already successfully implemented best practices to reduce its carbon impact throughout the whole supply chain; not only is this for business reasons but also in response to customers' growing attention to sustainability matters [58].

In 2020, the solar industry collaboratively finalised a roadmap of key sustainability metrics for the sector, creating NSF 457: Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters [59]. This includes reporting, among others, on the CF (i.e. global warming potential) and voluntary documentation of industrial leadership to reduce the carbon impact. In 2022, the Solar Stewardship Initiative [60] was launched to lead the industrial developments towards a responsible, transparent and sustainable value chain. On top of that, an increasing number of solar manufacturers are taking binding pledges to source 100% renewable electricity in the production process in the next decade, including the biggest players on the market, such as Longi (CN) and Jinko Solar (CN).

4 | ENVIRONMENTAL SUSTAINABILITY OF PV MANUFACTURING

In the following section, the authors look into the main drivers of the environmental impacts of the PV module manufacturing, in particular in relation to the CF, analyse the current trends and conclude on the opportunities for the net-zero transition in the future.

In the existing literature, the environmental impacts of the PV manufacturing are well documented [67–69]. The hotspot analysis was also a subject of an analysis in the preparatory study [8] conducted by the European Commission in the context of setting the ecodesign requirements. The GHG and particulate matter emissions in the manufacturing phases, has been identified as the major environmental impact categories for the PV modules.[††]

In fact, looking at the contribution analysis for a monocrystalline PV panel (i.e. how much different processes in the life cycle of the panel affect a certain impact category), climate change is influenced by electricity consumption and all main manufacturing processes (such as aluminium ingot production, solar glass production and steel

[††]These impact categories are also confirmed in the Product Environmental Footprint Category Rules (PEFCR) for PV modules [94, 95].

TABLE 3 PV modules manufacturing capacity and carbon footprint by country in 2021,

	Module production (GW)	Market share	Share of low-carbon electricity	kg CO_2eq/m^2	kg CO_2/m^2 reduction potential	Total CF (Mt)
China	181.8	75%	34%	143.66	72.2	124.97
Xinjiang, Jiangsu	—	—	25%	150.30	81.6	—
Vietnam	16.4	7%	43%	136.90	62.5	10.74
Malaysia	9.1	4%	19%	154.63	87.8	6.73
South Korea	8.0	3%	33%	143.94	72.6	5.51
USA	6.6	3%	40%	139.24	65.8	4.40
India	5.1	2%	22%	152.62	85.0	3.72
Thailand	2.9	1%	15%	158.29	93.1	2.20
Europe	2.2	1%	55%	127.16	48.6	1.33
Taiwan	2.2	1%	15%	157.84	92.4	1.65
Japan	2.2	1%	29%	147.25	77.3	1.54
Singapore	1.2	1%	2%	167.85	106.7	0.97
Canada	0.5	0%	82%	106.77	19.5	0.25
Total	242.3					164.00

Source: Own estimates.

production). On the other hand, particulate matter impact is mainly affected by electricity consumption. In this sense, the climate change impact category provides a more comprehensive assessment than particulate matter for monocrystalline PV panels. Climate change is also internationally known as a robust and well-established impact category; it is considered relevant in European policies such as the Green Deal [6] and Fit for 55 [18]. Furthermore, the climate change impact assessment method is also continuously updated in the scientific literature (thanks to IPCC regular reports) and in the environmental footprint (EF) method (last updates implemented in the EF package 3.1 in 2021), whereas the last particulate matter update dates back to 2016. For these reasons, the climate change impact category (i.e. CF requirement) was chosen as the environmental criterion to be considered in this paper. That said, it has to be acknowledged that looking into GHG emissions does not represent the complete picture of all the environmental impacts from PV manufacturing.

The CF of a PV module in physical terms is largely dependent on two parameters: the content of silicon in the panel and the share of low-carbon electricity used for its manufacturing [5]. However, from an energy perspective, the efficiency/yield of the panel could be included as a third influential parameter, as for the same amount of energy the number of PV modules required would be smaller. By taking the CF of some PV panels and conducting a multivariable regression model with these parameters, we developed a simplified model to estimate the CF of any given module (see Appendix A) [70].

Global PV module production in 2022 was in the range of 350–370 GW [2], with three quarters of the modules manufactured in China, while Europe produced only 1% or 2.2 GW. The average content of Si in the modules was approximately 580 g/m^2 [71], and the average efficiency of the PV modules reached 20.9% [71]. Taking the share of low-carbon electricity in the energy mix of the different manufacturing countries in 2021,[‡‡] a representative figure of the CF of PV modules for each country can be obtained. The modelling data used for the regression model based its CF calculations on the assumption that the entire PV manufacturing value chain is located in the modelled country (see Appendix A). Nevertheless, today China controls 97% of the market in the wafering phase [72], which accounts for a large portion of total energy consumed for the manufacturing of PV [72]. Thus, to better reflect the current state of PV global value chains, 30% of the CF of any given country in the table below is dependent on the energy mix in China.

The total CF is calculated as the equivalent PV area (m^2) of the module production capacity (GW). To do so, we assume an average module area of 1.657 m^2 and 346.3 W of rated power for a module with 20.9% efficiency. Consequently, any improvement in the panel's efficiency encompasses a higher rated power of the panel for the same surface area of the module, thus effectively reducing the total CF.

The CF of a PV fully manufactured with low-carbon energy sources with the described 2021 specifications is 71.5 kg CO_2/m^2. Hence, we can define the carbon reduction potential of any manufacturing country as the difference between this CF and the one corresponding to the energy mix of the manufacturing country.

According to these estimates, the average CF of a panel in 2021 was 143.93 kg CO_2/m^2 (see Table 3 for average CF per country) This average used China's overall national share of low-carbon electricity; nevertheless, as mentioned previously, most of the PV production in China takes place in the regions of Xinjiang and Jiangsu, with a more intensive carbon energy mix than the national average as illustrated in the table above. When using this mix as representative of Chinese

[‡‡]Ember database.

TABLE 4 Impact of different PV design and manufacturing improvements on the 2030 carbon footprint of the PV industry.

	No changes	Si content reduction	Improvement of the mix	Improvement in efficiency	Combined effect	30% share renewables in electricity used in manufacturing
Global CF PV manufacturing (Mt)	426	373	378	351	273	239
CO_2 reduction	0%	12%	11%	18%	36%	44%

production, the global CF increases by 5% to 173 Mt CO_2, with the average panel having a 151.84 kg CO_2/m^2 footprint. Meanwhile, the effect of fully greening the electrical input of PV manufacturing would equate to a 50% reduction in PV global emissions or 82.91 Mt CO_2eq.[§§]

In its roadmap to achieve net zero by 2050 [50], the IEA estimates that a 630 GW annual addition of PV capacity by 2030 is necessary to reach climate neutrality. This threefold expansion of PV manufacturing for 2050 Net Zero would consequently impact on the total global emissions of this sector. Ceteris paribus, this new manufacturing capacity corresponds to 426 Mt of CO_2 emissions yearly. When considering the most optimistic scenarios [73] in terms of prominence of PV technology (up to 2.4 TW[¶¶] of annual installed capacity by 2035), the total yearly emissions (ceteris paribus) could reach 1600 Mt of CO_2. However, the PV industry is highly evolving, with a roadmap of major improvements in the product design and the manufacturing process in the coming years. The industry plans to maintain the current pace of improvement of the average efficiency of the modules with 0.5% increments of efficiency annually, thus reaching a 25.4% average efficiency by 2030. Additionally, all wafer formats will consume significantly less silicon within the next 10 years. The expected reduction is in the range of 25% [71], attained by improvements in crystallisation and wafering yields and further reductions of the kerf losses and, most importantly, by a continuous reduction of the thickness of the wafer. Finally, as countries starts to decarbonise their energy sectors, a higher share of low-carbon energy of at least +15% is to be expected by 2030.

In the table below, we illustrate the effect of each of these individual improvements as well as the combined effect of all of them.[##] The best single measure to reduce the CF of the PV industry is to improve the energy efficiency of the panels, as it reduces the amount of modules needed to achieve the same energy; this measure is followed by the 25% reduction of Si content and the +15% improvement in the share of low-carbon sources in the energy mix with almost similar effects. The combination of all these improvements results in a 36% reduction of the footprint (see Table 4). Therefore, even tripling the amount of PV manufacturing output, the most probable outcome is that it will only increase the industry CF by 150%. Moreover, if we consider the voluntary industry pledges, such as the one noted in Table 2, for full renewable manufacturing of PV modules, further improvements of the CF can be expected. To illustrate this, we assume 30% of global PV modules[***] are produced with 100% low-carbon energy sources. This final scenario that combines the effect of the foreseeable improvements in PV technology and processes in the industry with a stronger push by the sector for greening their manufacturing generates an extra +8% CO_2 reduction with respect to the scenario without changes. Every additional 5% of fully renewable manufacturing represents a total of 5.72 Mt of CO_2 emissions avoided annually.

To conclude, some considerations are needed to relate the GHG emissions of the manufacturing phase of PV modules with the electricity produced by the modules themselves once installed.

The energy required for the production of PV modules requires on average about 1 year of use [47] before the break-even point is reached—the 'energy payback time'. However, it has to be noted that there is no direct compensation between the energy produced by the PV modules during their lifetime and the emissions due to their manufacturing (i.e. the emissions for the manufacturing of the PV module are in any case dispersed in the atmosphere). The manufacturing process requires a considerable amount of energy within a very limited amount of time and in a specific geographical location, whereas the energy produced by the PV module should be (typically) dispatched to the electricity grid over a long period of time (30 years). Therefore, assuming that either way PV modules will be used, it makes sense to promote the use of panels that have lower emissions during manufacturing.

5 | DISCUSSION AND CONCLUSIONS

With the expected increase of global PV capacity and the simultaneous tightening of emission targets, the contribution of PV module production to total global GHG emissions could become very significant.[†††] At the same time, many countries and regions produce PV modules with a carbon intensity that is below the current world average, even within China (e.g. Qinghai and Sichuan), suggesting significant scope for emission reductions [1].

[§§]Evidence from the industry suggests Europe's total PV modules manufacturing capabilities are around 9.2 GW (EU Solar Manufacturing Map, by Solar Power Europe, accessed December 2022). However, the value shown in the tables represents the total manufacturing output in the year 2021 as opposed to the total manufacturing capacity of Europe.
[¶¶]The report refers to 3 TW annual solar PV capacities by 2035 in direct current (DC). The value was reallocated to alternating current (AC) with a factor of DC/AC = 1.25.
[##]The assumptions for the calculation in the regression model is provided in Appendix A.

[***]This proportion is equally applied among all the different manufacturing countries.
[†††]According to a researcher of the US National Renewable Energy Laboratory (NREL), 'as much as a sixth of the remaining [global] carbon budget could be used to manufacture PV modules' [69].

A key conclusion drawn by the IEA is for policymakers to ensure that 'PV manufacturing facilities adopt low-carbon and material-efficient manufacturing practice'. This request is not in conflict with the fact that solar PV, compared with other electricity sources, has some of the lowest life-cycle GHG emissions per kilowatt hour generated. It merely reflects that GHGs need to be significantly reduced and that mitigation options in all sectors must be pursued if global climate targets.

In the absence of systematic regulatory measures, and considering the industry's preparedness to adopt cleaner production practices, there is now a unique opportunity for the transformation that needs to happen in the PV manufacturing phase. In this context, the Ecodesign and energy labelling requirements for PV modules and inverters currently under analysis by the European Commission [20] and in particular the need for compulsory requirements on the CF of (the manufacturing phase of) PV modules are of great importance.

These requirements should 'translate' into regulatory terms, with compulsory rules uniformly applicable on the EU internal market, and include the improvement potential of the three most promising avenues towards decarbonised PV manufacturing, that is, reduction of silicon content, increase of the energy yield of the PV module and decrease of the carbon intensity of the energy used during the manufacturing process. There are multiple policy approaches that could be implemented in this regard [44], including (a) quantitative requirements establishing a maximum admitted threshold for the carbon footprint of PV modules; (b) quantitative requirements for specific relevant parameters influencing the CF, such as the silicon content or the module yield; (c) information requirements on the CF of PV modules; and (d) CF information to be reported on the product information sheet that would accompany a potential energy label of PV modules. These mandatory measures would be instrumental to:

- foster further innovation in the design and manufacturing stage and promote the use of renewable energy for their production;
- (in the case of information requirements under Ecodesign or within the product information sheet accompanying an energy label for PV modules) provide a common reference for potential buyers to compare different products; such standardised pieces of information could also serve as tools for green public procurement schemes; and
- (in the case of maximum threshold requirements) ensure that only those products that meet a minimum level of ambition in emissions reduction are available on the market.

Whatever the chosen policy approach, it is considered necessary to have third-party verification of the CF calculation. This would considerably help in ensuring a consistent assessment of conformity assessment (i.e. the verification of the product's compliance with the given requirements).

5.1 | Future research directions

Extensive research on sustainability-related aspects of PV technology, across the various stages of its life cycle, already exists [67–69]. While technology is rapidly being deployed on a global scale, new challenges in terms of resource efficiency, waste management and environmental and social impacts are emerging. Notably, recent studies forecast the need for 486 million tonnes of aluminium to meet PV production growth rates [74, 75]. Recent studies have also highlighted the importance of focusing on the social impacts associated with PV manufacturing, notably in China, where large shares of global production are concentrated, considering, for example, the industry contribution to employment, labour impact and human rights [76, 77]. More research on the subject continues to be necessary [78, 79]. The analysis put forward by this article contributes to these efforts while providing a potential targeted scope for follow-up analysis. Future research might push our work in the following directions.

A first direction, focusing on the EU, could investigate the nexus between policymaking and industry action. The main pieces of EU policy relevant for the sustainability of PV technology include the upcoming Ecodesign Regulation [8, 80] and the Directive on Waste from Electric and Electronic Equipment (WEEE) [81]. The former focuses on the durability and carbon footprint of new products put on the EU market, while the latter focuses on collection, reuse and recycling targets for WEEE, which includes PV. However, how these regulatory measures for sustainability exactly affect EU industry players in the PV value chain is not entirely clear [82]. Sustainable and circular business models in the EU PV industry are now emerging, potentially bringing positive environmental as well as social impacts (e.g. recycling of PV panel materials by waste management companies; collecting and repairing old panels to enable reuse in social housing complexes and schools in the EU as well as overseas to provide an energy supply in rural areas; etc.), partly driven by regulation, and partly by new economic opportunities [83, 84]. More research on the circularity of PV is needed to achieve the full sustainability potential, further analysing the content of existing policy documents, literature, patents and projects in depth [85, 86]. Additionally, future empirical research might provide deeper insight into these business models and how they work, the drivers and barriers affecting their implementation [87, 88], as well as into their matches and mismatches with policy measures [82], and expected environmental impacts. This research might be carried out combining a qualitative approach based on stakeholder consultation (i.e. interviews, workshops) to consolidate an understanding and categorisation of these models across the EU industry, integrated with a quantitative approach (i.e. life-cycle assessment, input–output economic analysis) to model the carbon emission reduction potential of different sustainability strategies, including recycling and reuse. We conclude by noting that focusing on circular economy strategies for PV module reuse and repair is highly relevant given the increasing amount of PV waste expected to arise in the future, and recycling challenges [71]. In this context, Nyffenegger et al [89] recently argued that PV module reuse business models may allow the exploitation of emergent market gaps and opportunities, leading to the optimisation of economic and environmental performance, the increase of material efficiency and a reduction of CF. To this end, they propose a taxonomy of emergent categories of circular business models for PV reuse and a list of factors influencing the uptake of related product-service-system (PSS) solutions. Future research might look deeper into how such emergent solutions may be scaled up on the market, also taking into consideration the policy context and expected review of the WEEE Directive [90].

A second direction, focused on China, could mirror the first one, aiming to gain deeper insight into local policies, the emergent sustainability trends in the industry (see Table 2 as an exemplary and preliminary analysis of this kind), and how they are shaped by the regulatory environment. Parallel work may also focus more narrowly on the sustainable business models emerging in China, mirroring the analysis outlined above (e.g. for recycling and reusing end-of-life panels) with an EU scope. Some work on PV-related sustainable business models in China exists, looking, for example, at new possibilities for geographic distribution of renewable energy generation, also driven by digital technologies [91, 92]. However, this has been emerging only recently, and the collection of empirical data remains a challenge [85]. Consequently, future research might focus on this aspect with an exploratory approach. Apart from the more in-depth desk research on provincial and local-level policies and available data, particularly in the most important provinces for PV manufacturing, field research to explore local authorities' and Chinese companies' current actions and plans on decarbonisation of the manufacturing process could be valuable information for EU policies, such as Ecodesign.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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APPENDIX A

The multiple regression model was run using the data for monocrystalline modules of 'Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive' [70] as input. The corresponding data are summarised in Table A1.

To obtain the basic CF (g CO_2eq), the above values normalised by the lifetime energy yield need to be multiplied by their energy efficiency index for a 30-year lifespan, 6730 and 5540 kWh for the high- and low-efficiency panels, respectively. The average of the resulting values represents the dependent variable (Y) that will be used as a sample to determine the carbon footprint (CF) for any given scenario of content of Si (Si) and percentage of low-carbon energy sources (lc).

The content of Si and the percentage of low carbon are interdependent values, that is, the higher the content of Si, the more influence a carbon-intensive energy mix will have on the final carbon footprint. To account for the interlink effect between these parameters, a third variable is created as the numerical product of the two values. The explanatory variables of the regression model are summarised in Table A2.

The resulting CF explanatory equation for the multiple regression model has the following structure:

$$CF = \beta_0 + \beta_1 \cdot lc + \beta_2 \cdot Si + \beta_3 \cdot lc \cdot Si$$

where the coefficient values are as follows (Table A3).

Finally, the resulting statistics assessing the explanatory quality of the model are presented in Table A4.

TABLE A1 Summarised data input from 'Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive'.

% of low-carbon energy sources in energy mix	Content of Si (kg/m^2)	Low-efficiency (5540 kWh) carbon footprint (CF) per lifetime (LT) yield (kg CO_2eq/kWh)	High-efficiency (6730 kWh) carbon footprint (CF) per lifetime (LT) yield (kg CO_2eq/kWh)
100%	0.58	0.0141	0.0114
100%	1.08	0.0189	0.0152
100%	1.58	0.0231	0.0191
21.4%	0.58	0.0298	0.0246
21.4%	1.08	0.0423	0.0350
21.4%	1.58	0.0548	0.0453
39.58%	0.58	0.0237	0.0124
39.58%	1.08	0.0332	0.0206
39.58%	1.58	0.0433	0.0353
8.47%	0.58	0.0305	0.0252
8.47%	1.08	0.0434	0.0359
8.47%	1.58	0.0562	0.0463
98.17%	0.58	0.0141	0.0116
98.17%	1.08	0.0189	0.0156
98.17%	1.58	0.0231	0.0191
0%	0.58	0.0356	0.0281
0%	1.08	0.0523	0.0402
0%	1.58	0.0632	0.0519

TABLE A2 Sample values for the multiple regression model.

[A] % of low-carbon energy sources in energy mix	[B] Content of Si (g/m^2)	[A] * [B] (g/m^2)	Carbon footprint (CF) (g CO_2eq)
100.00%	580	580	7718
21.54%	580	124.93	165 325
39.58%	580	229.56	107 375
8.47%	580	49.13	169 283
98.17%	580	569.39	78 091
0.00%	580	0	193 186
100.00%	1080	1080	103 059
21.54%	1080	232.63	234 834
39.58%	1080	427.46	169 125
8.47%	1080	91.48	240 552
98.17%	1080	1060.24	103 732
0.00%	1080	0	274 486
100.00%	1580	1580	128 259
21.54%	1580	340.33	304 231
39.58%	1580	625.36	238 716
8.47%	1580	133.83	311 352
98.17%	1580	1551.09	128 259
0.00%	1580	0	350 128

TABLE A3 Coefficient values for the CF explanatory equation.

Coefficient	Value
β_0	87780.96
β_1	−46597.42
β_2	159.61
β_3	−107.34

TABLE A4 Multiple regression statistics.

Multiple R	0.988
R square	0.976
Adjusted R square	0.971
Standard error	14311.39
Observations	18