Barriers on PV trade will impede global carbon mitigation and local pollutant emissions reduction

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Abstract

The global trade of solar photovoltaic (PV) products substantially contributes to the increases in solar power generation and carbon emission reduction. This paper depicts the global PV product trade patterns and explores the emissions reduction potential, evaluates the impeding effect of tariff barriers on global PV product trade and the emissions reduction. In 2014 and 2017, the application of traded solar cells and modules resulted in emissions reductions of up to 840.71 and 1,734.59 Mt CO_2e as well as substantial reductions in local pollutants. From 2017 to 2050, traded solar cells and modules will result in an approximately 55.76-86.45 Gt CO_2e reduction. Extra-tariff imposition in its worst situation will result in global PV applications decreasing by 7.06% and carbon emissions mitigation potential decreasing by 5.09-7.89 Gt CO_2e by 2050. Well-coordinated policy and institutional reforms are recommended to facilitate PV product trade and deliver related global and local environmental benefits.

The Intergovernmental Panel on Climate Change (IPCC) claims that reducing greenhouse gases (GHGs) to net zero is important to limit global warming within 1.5°C to achieve sustainable development and predicts that 38-88% of primary energy and 59-97% of electricity must come from renewable resources by 2040-2055 [1].Solar power is expected to play a key role in facilitating this low-carbon transition, mitigating climate change and meeting energy demands [2-4]. During 2007-2017, the global annual installed PV power capacity increased from 2 GW to 103 GW, and global PV cumulative installations increased from 8 GW to 409 GW [5]. In 2007, global PV power generation was 7.48 TWh, only 0.04% of total production, which surged to 443.55 TWh in 2017, accounting for 1.72% of total amount [6]. Fast development of international trade contributes substantially to global PV product production and application expansion. The traded capacities of solar cells and modules increased significantly from 44.59 GW in 2014 to 79.65 GW in 2017, accounting for 25.02% and 19.47% of the global cumulative PV capacity installation in the corresponding years, respectively. Almost 100% in 2014 and 76.89% in 2017 of the newly installed global capacity were related to traded solar cells and modules, and this ratio was 96.19% in 2018 [7], indicating a significant role of international trade in promoting global PV power application (see Supplementary Data 1-2 for more details).

Studies have been conducted varying from calculating the lifecycle emissions and emission reduction potential of PV products [8-21] to PV product trade patterns and structures [22] to the emissions embodied in the bilateral PV product trade [23] and to the environmental impacts of the PV product trade [13,14,24]. Studies have also been carried out in various countries [15-21,24], concluded that PV power generation could indeed help to reduce carbon and local air pollutant emissions obviously. Although PV power generation has nearly ‘zero emissions’ in its operation [15,16], pollutant emissions cannot be ignored when considering the whole lifecycle of PV products--from ore mining, silicon and silicon wafer processing, and solar cell and PV panel producing [8,9,11,25]. With the development of international trade and production specialization [26,27], studies have focused on the solar module trade and accounting for the embodied carbon [22,24,28]. There has been widespread worry that PV product production “migrates” and is concentrated in certain countries/regions forming “hot spots” or “pollution havens” [24], while PV panels are imported and consumed by other countries/regions to generate clean electricity, which not only reduces carbon emissions but also helps to improve the local environment. This situation is often described as being “unfair” or “unbalanced” international trade in terms of environmental benefits [29-32]. However, previous studies concentrated on only a specific PV product and a limited subset of countries/regions without full consideration for the whole production and supply chain from a global perspective. And there was few literature exploring the impacts of trade restriction measures on the PV product which could lead to less PV power generation and emission reduction potential.

With international solar PV product market expansion, protectionism grew in the form of antidumping or countervailing measures on PV modules. Recent examples of these tensions include conflicts between the USA and China, the EU and China, etc.[5,33]. In 2017, the USA initiated the "301 Investigation" against China on imported goods (solar panels included) and led to a series of conflicting trade measures in between the two globally largest trade partners and spilled over to other economies, including EU, Canada and Mexico [34-38]. Most literatures concentrated on the economic impact of the USA-China trade war [37-45], only a few literature noticed that trade war was also likely to affect environment through changing global supply and consumption chain [46], and less conducive to clean energy development in less-developed regions[47]. When it comes to PV products trade, very few literature paid attention to the negative effects of trade war on PV product trade, production and application[48], cutting into global emissions reduction potential.

This study will focus on the emission reduction potential of global PV product trade and the extra trade barrier on PV product to fill in the literature gap. This study constructed a trade flow matrix (TFM) of PV products (see Methods for details). Then, embodied carbon and pollutant flows in the PV product trade were calculated, and the emissions reduction potential of PV power generation application related to PV product trade was estimated considering the country-/economy-specific situation as much as possible. A computable partial equilibrium (CPE) model was applied to disclose how the extra trade barrier can deteriorate the global mitigation potential (see Methods for details). We found that in 2014 and 2017, 75.28 and 121.77 Mt CO_2e were embodied in the global PV product trade, respectively, but the application of traded solar cells and modules resulted in emissions reductions of up to 840.71 and 1,734.59 Mt CO_2e as well as substantial reductions in local pollutants over their lifetime. From 2017 to 2050, traded solar cells and modules will result in an approximately 55.76-86.45 Gt CO_2e reduction. The results clearly show that trade protectionism cannot only harm the global PV product trade but the environment. Extra-tariff imposition in its worst situation will result in global PV applications decreasing by 7.06% and carbon emissions mitigation potential decreasing by 5.09-7.89 Gt CO_2e by 2050.

Results

Global PV product trade pattern

In this study, TFMs based on export and import trade values were constructed for 2014 and 2017. This study mainly adopted export values to construct TFMs and to carry out trade flow calculations and analyses for various regions and economies (see Table 1 for detailed region descriptions).

Table 1 Trade partners identified in PV product trade flow matrix (TFM).

Group of trade partners	Country/Economy
Oceania	Australia, New Zealand
Europe	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Russia Federation, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Southeast Asia and other Asian Countries	Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Vietnam, India, Turkey
America	Brazil, Canada, Mexico, USA
East Asia	China, Hong Kong, Taiwan, Japan, Korea
ROW	Rest of the world

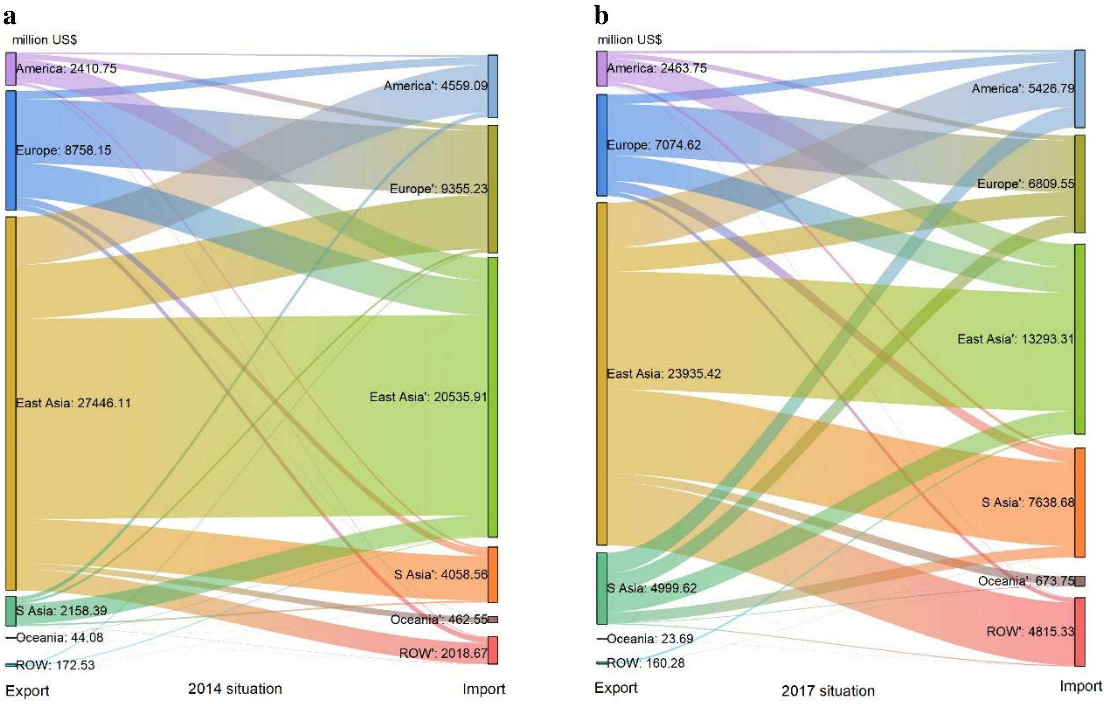
Note: Turkey is classified into "Southeast Asia and other Asian Countries", because its territory is mainly located in Asia area.

East Asia ranked as the top PV product exporter at US$27.45 billion (2014) and US$23.94 billion (2017), accounting for 66.96% and 61.92% of the global total, respectively, and East Asia was followed by Europe. Specifically, China was the largest exporting country, with US$16.30 billion (2014) and US$14.04 billion (2017), accounting for 39.76% and 36.32% of the global total, respectively. In 2017, Southeast Asia and other Asian countries (i.e., Southeast Asia plus India and Turkey) emerged as the 3rd largest exporter group, with an export value of US$4.99 billion.

For PV product trade inflows, East Asia was also the largest importer, with 50.10% and 34.39% of the global total in 2014 and 2017, respectively. Japan, China and the USA were the top 3 importing countries in 2014 and 2017. In 2017, Southeast Asia and other Asian countries surpassed America and Europe and became the second largest importer. The most noticeable trade flows were related to East Asia. Intra-east Asia trade stood out at US$14.72 billion in 2014 but decreased to US$8.25 billion in 2017. East Asia-Europe trade and East Asia-America trade were also important, amounting to US$1.65 billion and US$3.14 billion, respectively, in 2017 (see Fig. 1). At the country/economy level, the largest bilateral export flows were from China to Japan (US$4.84 billion, 2014) and from China to India (US$2.72 billion, 2017). (see Supplementary Data 3-4 for more details)

In both years, East Asia, Europe and America were major silicon suppliers, accounting for over 95% of the global share. The USA, Germany and Korea each accounted for over 20% of the global export market share. East Asia, Europe, Southeast Asia and other Asian countries were the top 3 exporters of silicon wafers in 2014 and 2017, with a total global export share of over 91%. China, Japan, and Taiwan were the most important silicon wafer providers, accounting for over 63% of the total silicon wafer export. East Asia, Europe, Southeast Asia and other Asian countries were also the top 3 exporters of solar cells and modules in 2014 and 2017, accounting for over 98% of the total exports. China, contributing over 45% of the trade value, was the largest exporter of solar cells and modules, followed by Taiwan.

In 2014 and 2017, East Asia was the largest importer of silicon (>80%) and silicon wafers (>50%), and Southeast Asia and other Asian countries stood out in silicon wafer imports, accounting for 15.69% and 22.22% of the global total, respectively. China, Japan, Taiwan, Korea and ASEAN countries were the major importers of silicon and silicon wafers as intermediate products. East Asia ranked first (at 40.93%) in 2014 and slipped to 5th in 2017 as a solar cell and module importer, owning to sharp import declines in Japan and China. Southeast Asia and other Asian countries as a group rose from 4th to 2nd place, mainly due to India's significant import increase. Europe and America were among the top 3 solar cell and module purchasers both years.



Global PV product trade value flow (export-import) based on TFM in 2014 and 2017

Fig. 1 Global PV installation and PV product trade flow. Sankey diagrams present global PV product trade flows in 2014 and 2017. Southeast Asia and other Asian countries is abbreviated as "S Asia". **a** This figure shows global PV trade flows in 2014. East Asia and Europe were the most important PV product exporters and importers. The top 3 biggest extra-region flows were from East Asia to Europe, then to America and to Southeast Asia and other Asian countries. **b** This figure shows global PV trade flows in 2017. East Asia was still the biggest PV product exporter and importer, and Southeast Asia and other Asian countries became the second largest importer. The top 3 biggest extra-region flows were from East Asia to Southeast Asia and other Asian countries, then to America and to Europe. From 2014 to 2017, the global PV trade flow pattern became more diversified and evenly distributed. East Asia maintained a leading role in the global PV product trade, especially China, which was the key PV product production and trade hub. Europe and America tended to produce and export silicon to and import solar cells and modules from Asia. Southeast Asia and other Asian countries increased their share in the global PV product market and intensified trade links with other regions, owing to local cheaper labour and land costs, lower tax rates, and less strict environmental regulation [30]. Import value gaps between East Asia and other regions narrowed (see Supplementary Data 5-10 for more details). This study converted all the currencies to US dollars first and then converted them to 2010 US$ for comparability.

Flow of embodied carbon and pollutants in the global PV product trade

The global PV product trade is accompanied by embodied carbon and pollutant emissions transfer. The carbon and pollutants embodied in PV products were calculated based on the global PV product TFM (see Methods for details) in 2014 and 2017.

Carbon emissions embodied in the global PV product trade were estimated to be 75.28 $MtCO_2e$ in 2014, which grew to 121.77 $MtCO_2e$ in 2017, accounting for 0.23% and 0.36% of the worldwide fossil fuel combustion carbon emissions in the same years [49], respectively. In 2014, silicon, silicon wafers, solar cells and module trade contributed 16.54 $MtCO_2e$, 17.63 $MtCO_2e$ and 41.11 $MtCO_2e$, respectively, and the corresponding quantities increased to 21.46 $MtCO_2e$, 31.83 $MtCO_2e$, and 68.48 $MtCO_2e$ in 2017 (Fig. 2a and 2b). East Asia was the largest exporter of carbon embodied in PV products, at 54.46 $MtCO_2e$ in 2014 and 85.33 $MtCO_2e$ in 2017, accounting for 72.34% and 70.07% of the global total, respectively. China, Taiwan and the USA were the top 3 carbon outflow economies, accounting for 70.85% (2014) and 67.19% (2017) of the global total. East Asia was also the largest embodied carbon importer, importing 42.60 $MtCO_2e$ (56.59% of global total) in 2014 and 47.19 $MtCO_2e$ (38.75% of global total) in 2017, followed by Europe (12.41 $MtCO_2e$, 16.49% of the global total) in 2014, and Southeast Asia and other Asian countries (25.91 $MtCO_2e$, 21.28% of the global total) in 2017. Japan and China were the top 2 embodied carbon importers in the two years. The largest embodied carbon flows in global PV trade were from East Asia to other regions, and from America and Europe to East Asia. In 2014, the largest carbon outflow was from China to Japan (9.88 $MtCO_2e$) and that in 2017 was from China to India (10.67 $MtCO_2e$). Fig. 2c and 2d presents the volume and direction of embodied carbon flow (see also Supplementary Data 11-12).

In 2014, East Asia and America were net carbon exporters whose balance of carbon emissions embodied in trade (BEET_C) (see Methods for more details) equalled 11.86 and 1.10 $MtCO_2e$, respectively, and Europe was the largest net carbon importer whose BEET_C was -4.81 $MtCO_2e$. In 2017, East Asia was the only net carbon exporter with a BEET_C of 38.14 $MtCO_2e$, while Southeast Asia and other Asian countries as a group was a net importer and expanded their BEET_C from -4.22 to -13.75 $MtCO_2e$ (Fig. 3a and 3b). China was the largest net exporter country, with BEET_C values of 21.97 and 37.23 $MtCO_2e$ in 2014 and 2017, respectively. The largest net importing country in 2014 was Japan with a BEET_C of -12.03 $MtCO_2e$, and in 2017, India was the largest net importing country with a BEET_C of -10.72 $MtCO_2e$ (see Supplementary Data 13).

In 2014, 12.69 Kt PM_{10}, 106.10 Kt NOx, 106.64 Kt SO_2 and 57.30 Kt COD were embodied in the global PV product trade. In 2017, embodied PM_{10} and COD increased by 6.02% and 94.49%, respectively, while embodied SO_2 and NOx decreased by 40.38% and 55.11%, respectively (see Supplementary Fig. 1). Pollutants embodied in solar cells and module trade had the most total embodied emissions at 50.49-64.23% of the emissions in 2014 and 66.02-73.27% in 2017. In general, East Asia far exceeded other regions in embodied PM_{10} (60.40%), NOx (87.34%), and SO_2 (79.30%) export in 2014 and had the largest export of embodied NOx (41.91%) in 2017. Europe was the largest exporter of embodied PM_{10} (38.08%) and SO_2 (35.43%) in 2017. In both years, China had the largest exports of embodied NOx (43.09% in 2014 and 22.96% in 2017), SO_2 (38.77% in 2014 and 13.88% in 2017) and COD (19.61% in 2014 and 17.03% in 2017), it was also the largest embodied PM_{10} exporter (29.47% in 2014 and 10.27% in 2017). East Asia and Europe were the main embodied pollutant importers. Southeast Asia and other Asian countries and America witnessed an obvious increase in embodied pollutant imports (Supplementary Data 14-19). Based on the balance of pollutant emissions embodied in trade (BEET_P) (see Methods), East Asia, represented by China, was the most significant net exporter of embodied PM_{10}, NOx, and SO_2 in 2014. Europe, Southeast Asia and other Asian countries were net exporters of embodied COD in 2014. In 2017, East Asia was still the largest net exporter of embodied NOx and became an embodied COD net exporter. Southeast Asia and other Asian countries as a group was the largest net exporter of embodied PM_{10} and SO_2 in 2017 (Fig. 3c and 3d, Supplementary Data 20-23)

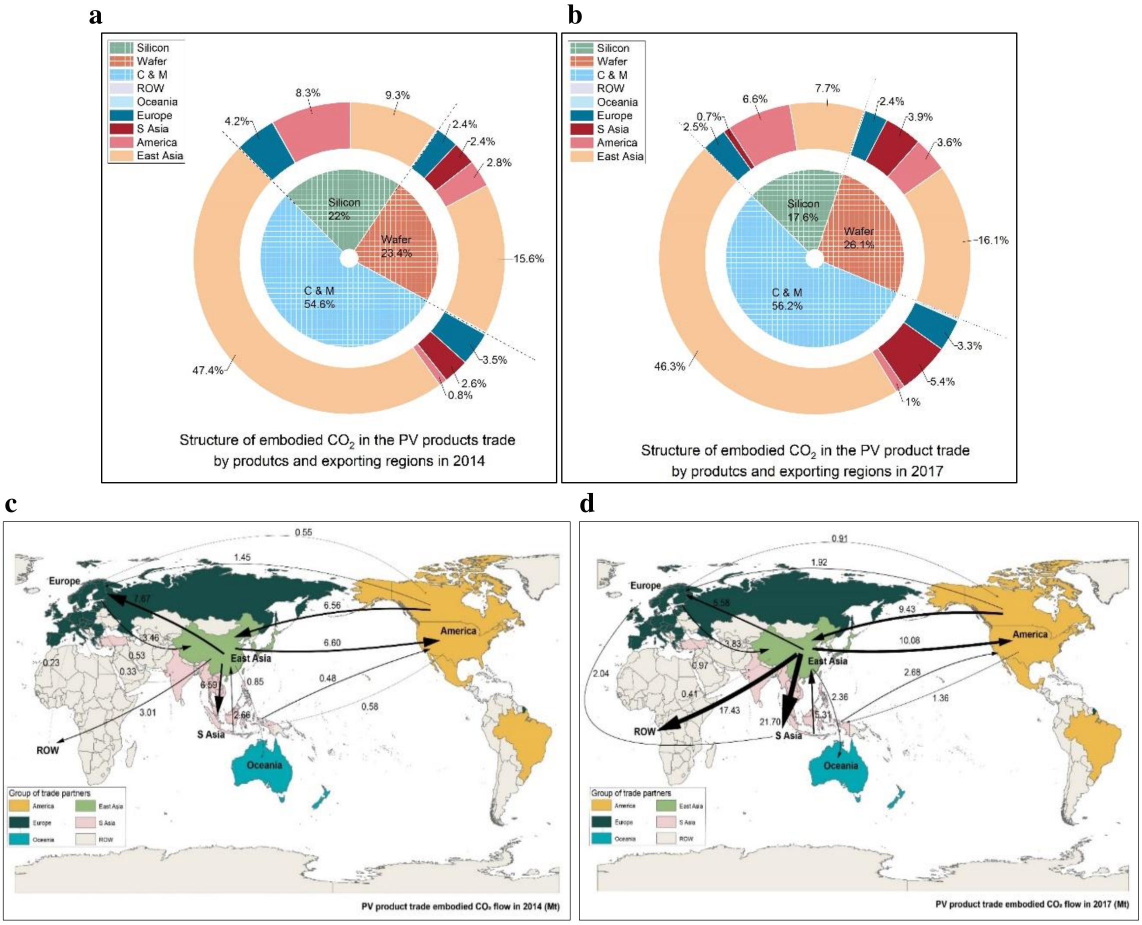
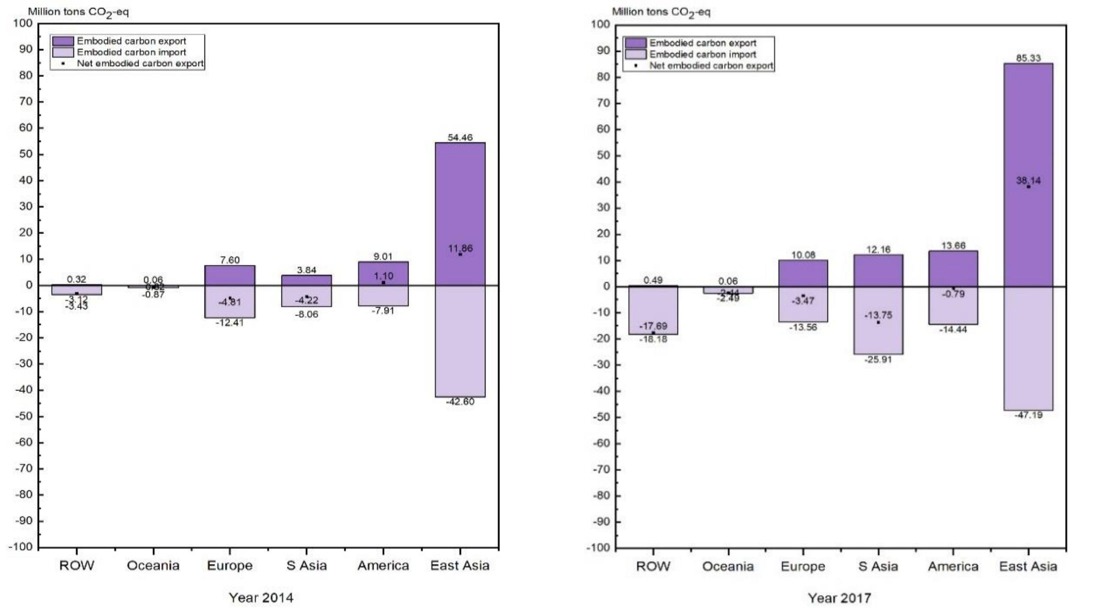


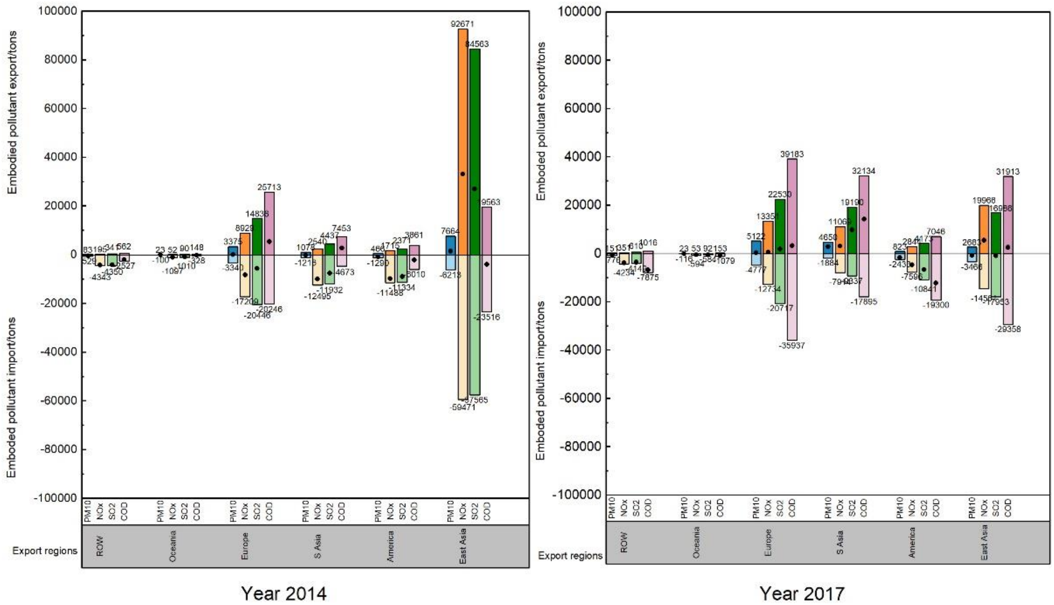
Fig. 2 Structure and flow of CO_2 embodied in the global PV product trade (2014 and 2017). These maps represent CO_2 embodied in the global PV product trade in 2014 and 2017. **a, b** In the two sub-figures, inner pies represent the proportion of carbon embodied in different PV product exports; outer doughnuts explain the proportion of embodied carbon contributed by each exporting region. **c, d** The two sub-figures represent flow of carbon embodied in PV product trade between regions in 2014 and 2017. From 2014 to 2017, noticeable growth in embodied carbon appeared in addition to an increase in PV product trade, especially in East Asia, Southeast Asia and other Asian countries. Compared with in 2014, in 2017, carbon emissions embodied in PV product trade increased by 61.76% or 46.49 $MtCO_2e$. East Asia observed the largest increase in embodied carbon exports (30.87 $MtCO_2e$), which increased by 56.68%, and its trade with Southeast Asia and other Asian countries contributed 15.11 $MtCO_2e$ to this increase. Southeast and other Asian countries had the second highest growth of embodied carbon exports at 8.32 $MtCO_2e$ and the largest increase rate at 216.79%. China accounted for the largest increment (20.65 $MtCO_2e$), followed by the USA (3.99 $MtCO_2e$) and Taiwan (3.84 $MtCO_2e$). The increase in Southeast Asian countries was conspicuous, e.g., Malaysia (3.10 $MtCO_2e$) and Vietnam (1.80 $MtCO_2e$). For embodied carbon imports, growth in Southeast Asia and other Asian countries was the largest (17.85 $MtCO_2e$), followed by that in America (6.54 $MtCO_2e$), and the leading countries were India, China and the USA (see Supplementary Data 11-12).

a **b**



Balance of CO_2 embodied in the PV product trade in 2014 and 2017

c **d**



Balance of local pollutants embodied in the PV product trade in 2014 and 2017

Fig. 3 Balance of CO_2 and local pollutants embodied in the PV product trade in 2014 and 2017. These column charts show the balance of total CO_2 and pollutants embodied in the global PV product trade by region, bars above the horizontal axis (y=0) represent CO_2 and local pollutants embodied in exports, and bars under the horizontal axis represent CO_2 and local pollutants embodied in imports. **a, b** Black dots represent the balance of embodied CO_2 ($BEET_C$). **c, d** Black dots display the balance of embodied local pollutants ($BEET_P$).

Status quo emissions reduction potential of trade-related PV application

PV power generation helps reduce carbon and pollutant emissions when it is used to replace local power generation, especially in grids where carbon-intensive thermal power dominates. This study assumes that imported solar cells and modules are applied locally to generate PV power and to reduce carbon and pollutant emissions.

The capacity of solar cells and modules globally traded in 2014 was 44.59 GW, their power generation potential totalled 1,136.75 TWh over a 30-year lifetime, accounting for 4.75% of world total electricity generation in 2014. In 2017, 79.65 GW of solar cells and modules was traded, which would generate 2,325.25 TWh during a 30-year lifetime, accounting for 9.10% of the global electricity generation in 2017 [49] (see Supplementary Fig. 2). East Asia contributed the most PV power generation potential from exported solar cells and modules, accounting for 72.92% of the global total in 2014 and 68.99% of the global total in 2017, followed by Europe (20.11% in 2014 and 15.53% in 2017). China was the largest contributing country, accounting for over 50% of the global total in 2014 and 2017. In terms of imports, the most substantial PV power generation potential took place in East Asia at 449.96 TWh in 2014 and in Southeast Asia and other Asian countries at 670.12 TWh in 2017. The largest PV power generation potential was in Japan (260.42 TWh) in 2014 and in India (435.37 TWh) in 2017(Supplementary Data 24).

Based on the potential of PV power generation, emissions reduction of traded solar cells and module application can be calculated for two PV power generation application scenarios, namely, substitution for electricity of the local grid (SSG) and substitution for thermal power generation (SST) (see Methods for more details). By producing clean solar power, solar cells and modules traded in 2014 could potentially reduce carbon emissions by 593.99 and 840.71 Mt CO_2e during the 30-year lifetime under the SSG and SST scenarios, accounting for 1.81% and 2.56% of global carbon emissions from fossil fuel combustion in the same year, respectively [49]. The corresponding carbon emissions reduction potential of solar cells and modules traded in 2017 under the SSG and SST scenarios increased to 1,194.23 and 1,734.59 Mt CO_2e, accounting for 3.57% and 5.19% of global carbon emissions from fossil fuel combustion in the same year, respectively. (see Table 2) East Asia contributed the greatest total carbon abatement potential in the two scenarios, ranging from 455.68 to 620.59 Mt CO_2e in 2014 and from 889.53 to 1,262.24 Mt CO_2e in 2017 through the export of solar cells and modules, and Southeast Asia and other Asian countries and Europe contributed the second and third highest total carbon abatement potential. China contributed the greatest carbon reduction potential, at 318.72-431.18 Mt CO_2e in 2014 and at 683.56-962.39 Mt CO_2e in 2017, accounting for over 50% of the global total. For the reduction beneficiaries, East Asia would receive the largest carbon emissions reduction potential of 255.05-330.01 Mt CO_2e by import in 2014, followed by Europe (114.23-197.61 Mt CO_2e). In 2017, Southeast Asia and other Asian countries ranked first in terms of receiving reduction potential at a 425.98-546.53 Mt CO_2e. (Fig. 4) More specifically, based on imported PV power generation capacity, Japan could receive a 141.09-167.67 Mt CO_2e reduction potential in 2014, and India could receive a 312.27-389.14 Mt CO_2e reduction potential in 2017, becoming the largest beneficiaries (see Supplementary Data 25 for more detail).

Apart from reducing carbon, solar power replacement of fossil fuel-fired power generation also leads to local air pollutant emissions abatement. By replacing local power generation, traded solar cells and module applications in 2014 would result in reductions of approximately 137.99-183.72 Kt PM_{10}, 1,110.00-1,604.62 Kt SO_2 and 848.24-1,194.22 Kt NOx in a 30-year lifetime under the SSG and SST scenarios; the corresponding estimations of the reduction potentials in 2017 increased to 794.94-1,039.68 Kt PM_{10}, 2,746.97- 4,095.61 Kt SO_2 and 2,365.43- 3,253.00 Kt NOx under the SSG and SST scenarios. East Asia's contributions to the pollutant reduction potential were the largest due to substantial exports from the region; the region accounted for over 75% of each pollutant reduction potential. Specifically, China's contribution to pollution abatement potential was the highest, followed by Taiwan, Germany and Korea. Southeast Asia and other Asian countries as a group was the largest beneficiary in most cases, acquiring an over 30% abatement potential for each pollutant. India benefited the most in terms of the largest emission reduction potential of all pollutants under the 2017 trade situation. Other major beneficiaries were the USA, Australia, Mexico, Turkey, and Vietnam (Supplementary Figs. 3 and 4, Supplementary Data 26-28).

Table 2 Lifetime CO_2 reduction potential from traded solar cells and modules of exporting region (Mt CO_2).

Exporting regions	SSG2014	SSG2017	SST2014	SST2017
Oceania	0.94	0.83	1.41	1.34
Europe	96.50	133.53	164.36	229.82
Southeast Asia and other Asian Countries	31.77	153.77	40.78	215.53
America	7.01	10.37	10.35	16.95
East Asia	455.68	889.53	620.59	1,262.24
ROW	2.09	6.19	3.22	8.72

This table represents the CO_2 emissions reduction potential of traded solar cells and modules over a 30-year lifetime, the SSG scenario represents the substitution of PV power for local grid electricity, and the SST scenario represents the substitution of PV power for thermal power generation.

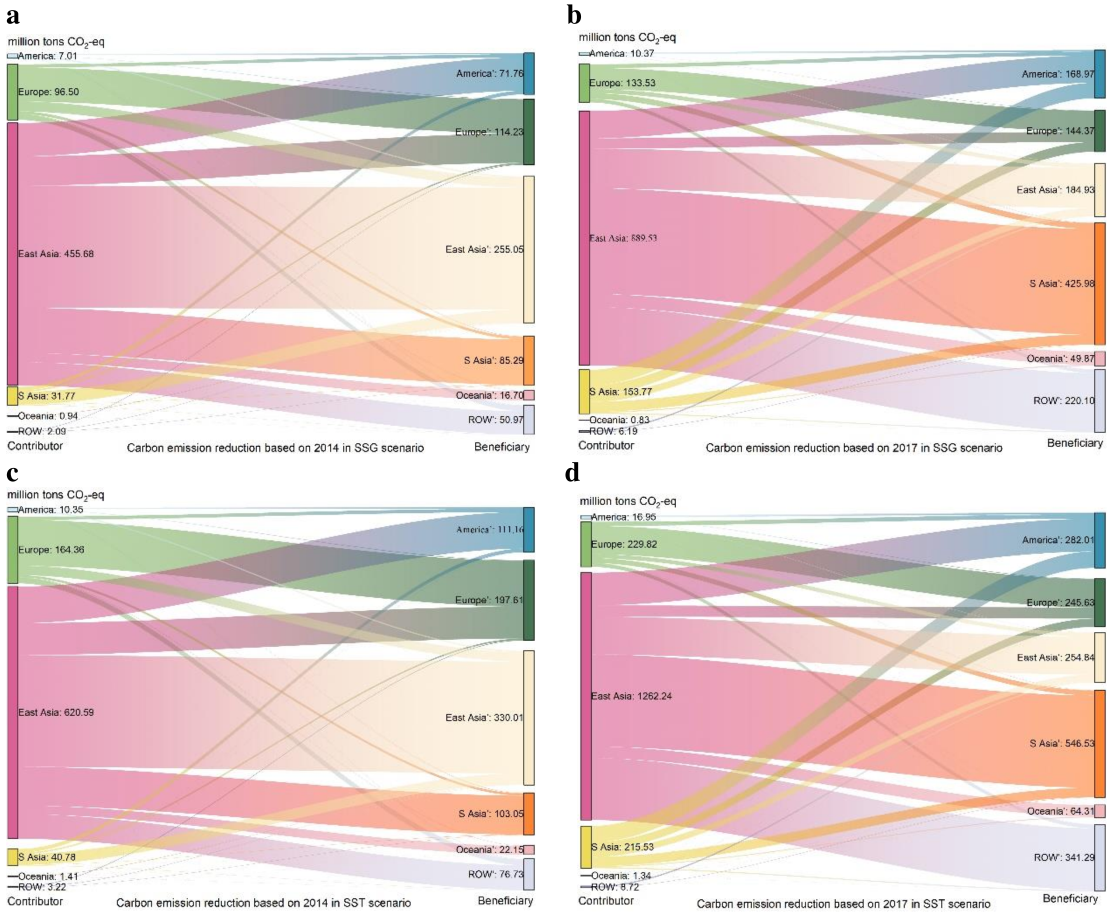


Fig. 4 Carbon emissions reduction potential of traded solar cells and modules in 2014 and 2017 (30-year lifetime; SSG and SST scenarios). a, b, c, d The Sankey diagrams show the CO_2 emissions reduction potential transferred from exporter regions (right) to importer regions (left) in 2014 and 2017 under SSG and SST scenarios.

Projection to emissions reduction potential of trade-related PV application

According to the IRENA [50] and our projections (see Methods and Supplementary Data 29), under the business as usual (BAU) scenario, global PV cumulative installation will increase from 409.10 GW in 2017 and reach 9,200.15 GW by 2050, cumulative traded PV modules will increase from 79.65 GW in 2017 to 7,073.66 GW in 2050, whose proportion in total PV capacity installation will substantially grow from 19.47% to 76.89% (Fig. 5a)

Under the BAU scenario, annual power generation from worldwide PV cumulative installation will increase from 390.22 TWh in 2017 to 8,775.54 TWh in 2050, those from traded PV modules will increase from 75.98 TWh in 2017 to 6,747.19 TWh in 2050. During the forecast period (2017-2050), global PV applications will cumulatively produce 144,104.43 TWh of electricity, and of that amount, traded PV modules will contribute 105,423.07 TWh (see Fig. 5b).

From 2017 to 2050, annual carbon reduction from global PV power generation under the SSG scenario will increase from 0.21 to 4.64 Gt CO_2e, and those under SST will increase from 0.32 to 7.20 Gt CO_2e. Traded PV will contribute 0.04-3.57 Gt CO_2e under the SSG, and that under SST will be 0.06-5.53 Gt CO_2e. Global PV utilization under the SSG and SST scenarios will cumulatively result in a 76.21-118.18 Gt CO_2e reduction during 2017-2050 (Supplementary Fig. 5a), in which traded solar cell and modules under the SSG and SST scenarios will result in an approximately 55.76-86.45 Gt CO_2e reduction (see Fig.5c and Supplementary Data 29).

From 2017 to 2050, annual pollutant emission reduction from global PV application under the SSG scenario will be 0.05-1.20 Mt PM_{10}, 0.25-5.57 Mt SO_2 and 0.22-4.99 Mt NOx, and those under the SST scenario will be 0.09-2.00 Mt PM_{10}, 0.42-9.55 Mt SO_2 and 0.35-7.98 Mt NOx. Contribution of traded PV will account for 0.01-0.92 Mt PM_{10}, 0.05-4.28 Mt SO_2 and 0.04-3.84 Mt NOx under SSG, and those under SST will be 0.02-1.54 Mt PM_{10}, 0.08-7.34 Mt SO_2 and 0.07-6.13 Mt NOx. During the forecast period, global PV utilization in the SSG and SST scenarios will result in cumulative emission reductions of 19.73-32.82 Mt PM_{10}, 91.48-156.74 Mt SO_2 and 82.02-130.99 Mt NOx (Supplementary Fig. 5b), of which traded solar cell and module utilization will account for cumulative emission reductions of 14.43-24.01 Mt in PM_{10}, 66.93-114.67 Mt in SO_2 and 60.00-95.83 Mt in NOx (see Fig. 5d and Supplementary Data 29).

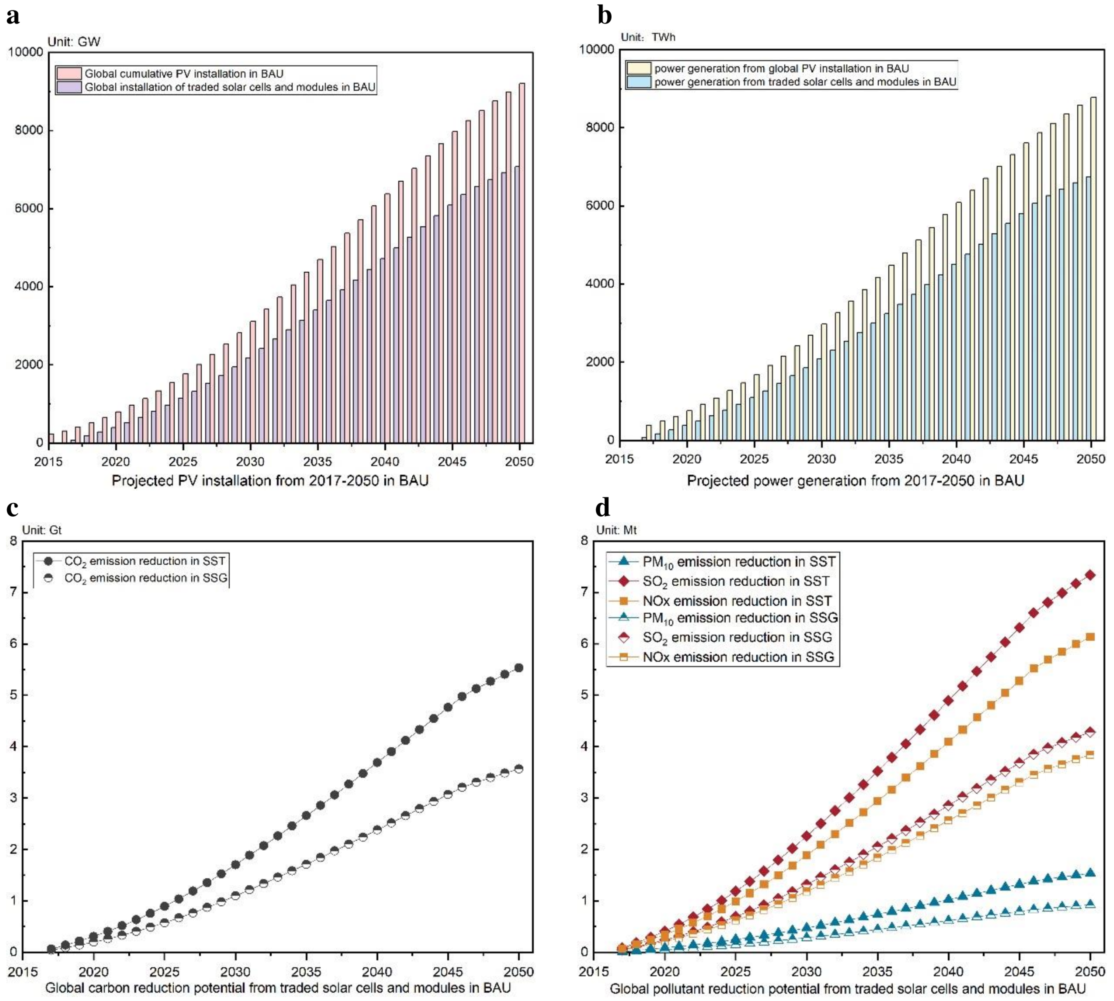


Figure 5 Global carbon and pollutant reduction potential from traded solar cells and modules in BAU. **a** Column chart shows projected global cumulative PV installation and traded PV capacity in the BAU scenario. Global cumulative installed PV capacity values from 2015-2017 were drawn from IEA-PVPS[5,7], and the capacity values from 2017-2050 were projected by the authors based on IRENA[50] (see methods for details). **b** Column chart shows projected power generation potential from globally cumulative PV installation and traded PV capacity in the BAU scenario. **c, d** These two figures show carbon and pollutant emission reduction potential from traded solar cells and modules from 2017-2050 in BAU.

Barriers to the PV product trade impede global emissions reductions potential

Considering the 2017 global PV product trade as a reference, compared with the BAU scenario, the worst trade barrier scenario (TBS) or extra tariff imposition scenario (see Methods for details) would reduce the global solar cell and module trade by US$3.61 billion, accounting for 15.34% of the 2017 baseline trade value. Exports from all economies would experience loss; for example, the export values for China, the Netherlands, Vietnam, Germany and Korea would decrease by US$799.03 million, US$585.93 million, US$482.64 million, US$337.79 million, and US$329.14 million, respectively, accounting for 7.41-38.36% of their 2017 baseline exports. Some countries/economies are expected to experience tremendous decline in solar cell and module imports with the 2017 baseline reference, and the largest declines would be seen in the USA (US$835.70 million, or 25.48% of its baseline import), India (US$739.43 million, or 26.50% of its baseline import) and the Netherlands (US$620.07 million, or 40.29% of its baseline import) (see Supplementary Data 30).

In terms of the 2017 baseline scenario, under TBS, extra tariff imposition would result in that, 22 countries/economies (including ROW-$_{CPE}$) of the top 25 PV product trade partners (including ROW-$_{CPE}$, see Methods for details), would experience annual solar cell and module output declines of 3.32-2,030.35 MW, and the largest decline will occur in China. Only 3 economies will slightly increase solar cell and module production by 35.66 - 271.88 MW. The USA would increase production the most. The global total solar cell and module output would decline by 7.31 GW, accounting for 7.06% of the global annual installed capacity in 2017 (see Table 3, Supplementary Data 30).

The reduction in global PV product output will then impede PV application and PV power generation and carbon emissions mitigation potential. Under TBS, the cumulative global PV power capacity installation by 2050 will be only 8,551.05 GW, a reduction of 649.10 GW, in which traded solar cell and module utilization will decrease by 914.03 GW and amount to 6,159.63 GW (Fig. 6a), and domestically supplied solar cell and module application will increase by 264.93 GW and amount to 2,391.42 GW. Under TBS, from 2017 to 2050, traded solar cell and module utilization will cumulatively produce 91,800.71 TWh, which is 13,622.37 TWh lower than that in the BAU scenario, and global PV applications will cumulatively produce 134,482.66 TWh of electricity, which is 9,621.77 TWh lower than that in the BAU scenario. (Fig. 6b)

Under TBS, from 2017 to 2050, global solar cell and module utilization in the SSG and SST scenarios will result in 71.12-110.28 $GtCO_2e$ cumulative mitigation, which is 5.09-7.89 $GtCO_2e$ less than that under the BAU scenario. Traded solar cells and modules will account for 48.55-75.28 $GtCO_2e$ in cumulative mitigation, which is 7.20-11.17 $GtCO_2e$ less than that in the BAU scenario.

(Fig. 6c) Under TBS, from 2017 to 2050, global PV utilization will result in cumulative mitigation of 18.41-30.62 Mt PM_{10}, 85.37-146.28 Mt SO_2, and 76.54-122.24 Mt NOx, which are less than that under the BAU scenario by approximately 1.32-2.19 Mt of PM_{10}, 6.11-10.47 Mt SO_2, 5.48-8.75 Mt NOx. Traded solar cells and modules will result in cumulative mitigation of 12.57-20.90 Mt PM_{10}, 58.28-99.85 Mt SO_2, and 52.25-83.44 Mt NOx, which are less than that under the BAU scenario by 1.87-3.10 Mt PM_{10}, 8.65-14.82 Mt SO_2, 7.75-12.38 Mt NOx (Fig. 6d) (see Methods and Supplementary Data 31).

Table 3 Changes in PV product exports, imports and outputs under TBS in contrast to BAU scenario (with 2017 reference)

Economy	**Change in export value (million US$)**	**Change in import value (million US$)**	**Change in output (MW)**
AUS	-1.77	-3.13	-4.21
AUT	-19.58	-57.24	-12.85
BEL	-40.52	-108.99	-31.52
BRA	-0.03	1.60	-7.74
CAN	-43.30	-1.42	-100.71
CHN	-799.03	31.34	-2,030.35
CZE	-37.04	-28.70	-94.24
FRA	-95.39	-265.53	-11.52
DEU	-337.79	-597.42	-464.19
IND	-51.37	-739.43	173.11
ITA	-73.34	-122.28	-104.61
JPN	-28.17	21.71	-155.20
MYS	-102.16	-2.97	-249.23
MEX	-6.51	-2.73	-15.44
NLD	-585.93	-620.07	-1,262.49
TWN	-226.24	-1.80	-561.20
POL	-13.84	-57.67	-3.32
KOR	-329.14	-11.18	-798.42
SGP	-101.61	-2.91	-251.17
THA	-22.02	2.92	-67.37
TUR	-0.17	21.90	-87.83
GBR	-47.34	-187.81	35.66
USA	-48.55	-835.70	271.88
VIE	-482.64	-7.79	-1,210.27
ROW-CPE	-113.36	-31.54	-266.14

This table shows changes in PV trade export value, import value and output of each economies under TBS. In the GSIM model, Hong Kong and China are incorporated as one economy, so their bilateral trade was treated as domestic sales. The ROW-CPE includes countries/economies other than the 24 largest PV product trade partners identified in the GSIM model and were treated as one economy. This study converted all the currencies to US dollars first and then converted them to 2010 US$ for comparability.

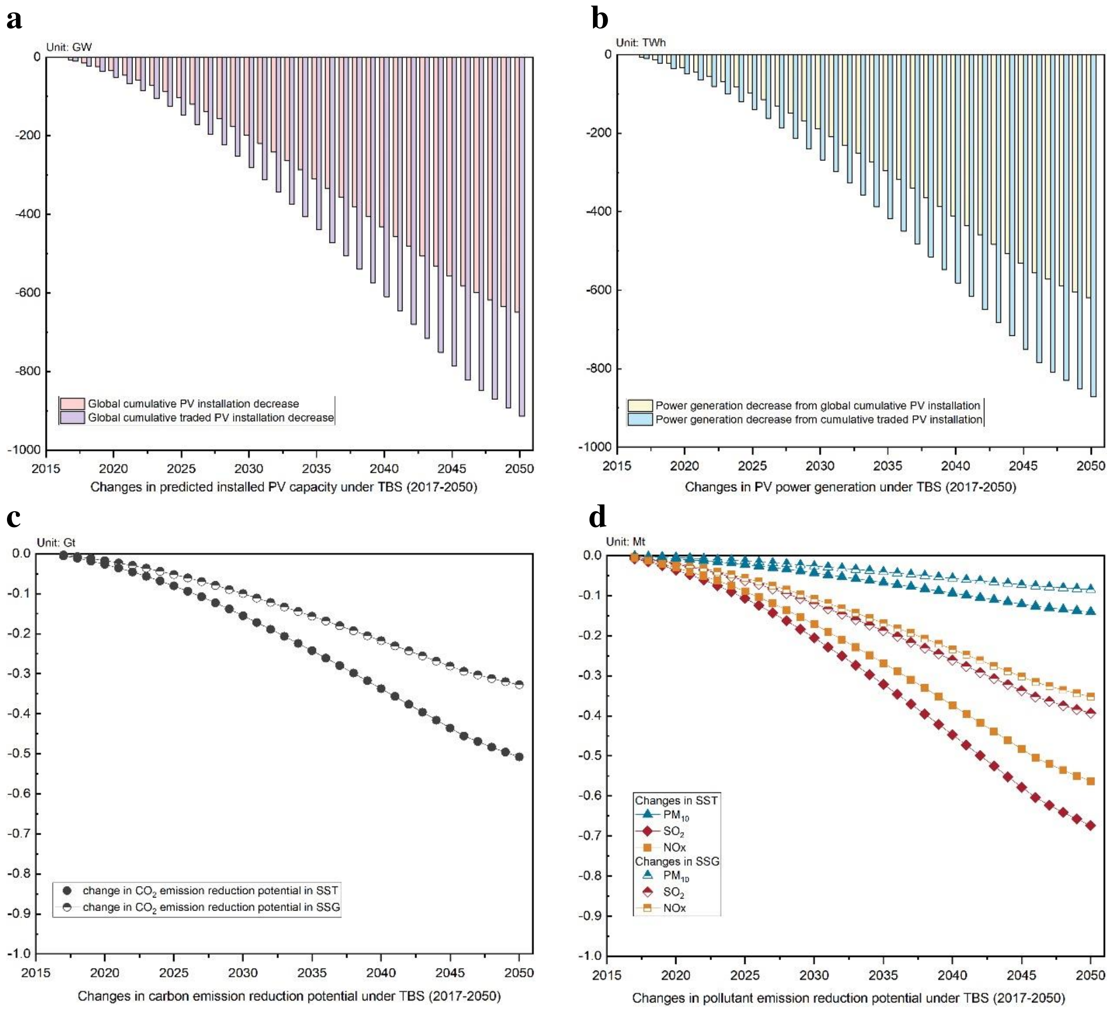


Fig. 6 Extra tariff impacts on the global PV capacity installation, PV power generation and emissions reduction potential (2017-2050) under trade barrier scenario (TBS). a, b Column charts show decrease of global cumulative PV capacity installation, traded PV capacity and the decrease of global PV power generation in TBS to represent the impacts of extra tariffs on PV product trade. **c, d** The point-line charts show the decreases in CO_2 and air pollutant emissions reduction potential in the SSG and SST scenarios due to the impacts of extra tariffs on PV product trade.

Discussion

The global solar PV product trade plays an important role in facilitating PV products production and utilization, mitigating climate change and improving local environmental quality. Traded solar cells and modules in 2014 and 2017 could generate 1,136.75 TWh and 2,325.25 TWh of electricity over their 30-year lifetimes. These environmental benefits are sizable and significant when considering that solar power could substitute for local power generation sources. The 30-year lifetime GHG emissions reduction potential from traded solar cells and modules could be as high as 840.71 Mt CO_2e for those traded in 2014 or 1,734.59 Mt CO_2e for those traded in 2017. From 2017 to 2050, globally traded solar cells and modules will cumulatively contribute 105,423.07 TWh of clean electricity and result in a reduction in emissions from the BAU scenario of approximately

55.76-86.45 Gt CO_2e.

The present study clarified that, although the global PV product trade is accompanied by carbon and pollutant emissions "migration", the embodied emissions in the global PV product trade are trivial compared with the substantial emissions reduction potential this type of trade can contribute to global public goods by helping to avert a climate crisis. Most of the countries/economies that were the major producers and exporters of PV products can also enjoy tremendous net environmental benefits in the form of pollutant emissions reductions from imported PV power generation capacity.

Trade protectionism measures, such as extra tariffs on PV products associated with the US-China trade war, will not only harm some specific countries/economies but also hurt the whole world by eating into the emissions reduction potential from PV product applications. Under the worst trade barrier or the extra tariff imposing scenario, from 2017 to 2050, global cumulative PV power production will be 9,621.77 TWh less than that in the BAU scenario, which will lead to a decline in the global cumulative emissions reduction potential of 5.09-7.89 Gt CO_2e, 1.32-2.19 Mt PM_{10}, 6.11-10.47 Mt SO_2, and 5.48-8.75 Mt NOx. Therefore, there is strong environmental cases for facilitating the trade of PV product trade globally.

There are also several policies and measures that could support the recommended facilitation of this trade. The most straightforward of these measures is lowering tariffs; however, this is very unlikely to happen without coordination from regional and global institutions. A concrete channel through which this coordination can occur involves incorporating PV products into the 'environmental products list' of the WTO and regional free trade agreements and excluding these products from protectionism and trade barriers. There is also a case for strengthening coordination between regional and global trade organizations and the United Nations Framework Convention on Climate Change (UNFCCC). For example, the UNFCCC could encourage countries to include the global and local impacts of PV product trade in their nationally determined contributions (NDCs) that countries pledged as part of the Paris Agreement. Finally, these efforts would be given additional support with enhanced coordination and information sharing across agencies responsible for the trade portfolio and climate change. All in all, analysis of this article can provide a firm evidence base for collaboration at multiple levels of decision, expanding the global solar PV product market and global and local emissions reductions.

Methods

The four major products in the global PV industry chain are silicon, silicon wafers, solar cells, and PV modules [5]. In the present study, solar cells and modules are treated as a whole set of product segments for convenience. Because international statistics on PV product production and trade in the early years were sparse and 2014 and 2017 set the historical records of 40 GW and 100 GW of newly installed PV power capacity, we chose these two years to carry out the global snapshot observations and then project to 2050. First, the major PV product trade partners whose cumulative share exceeded 80% were chosen for each product based on ABRAMS world trade wiki [51]. Second, country/economy-specific PV product trade data were extracted from the UN Comtrade database [52] and national official statistics to construct the TFM for the description of the global PV product trade situation. Third, the embodied carbon and pollutants in each product's trade network were calculated. Fourth, the emissions reduction potential of PV power generation based on the application of the traded PV products was predicted. Finally, a computable partial equilibrium model, the global simulation model (GSIM), was applied to simulate the impact of trade barriers on the PV product trade and the loss in emissions reduction potential.

Multi-lateral PV product trade and trade flow matrix (TFM) construction

Research on international trade and environmental issues usually employs the multiregional input-output (MRIO) method and data [29-32,53-55]. Global MRIO data such as GTAP, WIOD, and Eora are based on macroeconomic sector data, from which information about PV products and their global trade was difficult to extract. Existing studies mainly refer only to trade statistics for solar modules to account for embodied carbon flow and covered only limited countries/regions[22,24,28], while few studies have focused on the environmental impacts of the global PV product trade.

To form a global PV product trade data set, this study processed a large amount of data obtained from multilateral institutional databases and databases of customs and trade departments from dozens of countries and economies [52,56-71] to construct a trade flow matrix (TFM) of PV products, which served as the basis to conduct calculations and analyses of embodied pollutants and emissions reductions related to PV application.

Harmonized System (HS) commodity codes were used to retrieve trade data for PV products (HS6 code, silicon-280461, silicon wafer-381800, and solar cells and modules-854140). More specific trade data with 8 or 10 digits were obtained from official statistics or customs of various countries/economies. Fifty-three countries/economies and the "rest of the world" (ROW) are included in the TFM, and they are divided into six groups/regions, namely, Oceania, Europe, Southeast Asia and other Asian countries (Southeast Asia plus India and Turkey), America, East

Asia, and ROW (see Table 1). ROW refers to all the countries/economies that are not explicitly identified and are treated as one group of trade partners.

We built TFM $A_{i,j}$ for each PV product category, where i denotes the exporting country/economy, and j denotes the importing country/economy. $a_{i,j}$, an element of $A_{i,j}$, represents the trade value of each product exported from i to j.

The trade values between ROW and other identified countries/economies were not known owing to limited information, so we estimated the export value from ROW to country j based on trade statistics (see Supplementary Note 1).

The trade value statistics obtained from various sources were in the current prices of various currencies. This study converted all the currencies to US dollars first and then converted them to 2010 US$ for comparability.

Existing PV product trade studies have mostly been conducted based on the UN Comtrade database, and few of these studies noted re-export and re-import problems in the database [22,28]. Proportions of re-export to total export value in some economies are quite considerable; for instance, in 2017, over 99% of the total value of solar cells and modules exported from Hong Kong were attributed to re-export, and in Canada and the USA, the proportions were both over 11%, which essentially can distort real global PV trade volume, making inter-country/region embodied carbon and pollutant flow estimations inaccurate. In this study, the export data were traced back and assigned to the actual sources (exporters) and destinations (importers) to construct an adjusted TFM (see Supplementary Table 1, Supplementary Note 2).

Accounting for embodied carbon and pollutant emissions in trade

PV power generation is relatively clean and near zero-emissions in its application, but certain amounts of GHGs and pollutants are emitted during the PV products production process [12,16,29,32]. The global PV product trade results in the dislocation of production and consumption, accompanied by embodied carbon and pollutant emissions flows and environmental benefits “redistribution”.

To calculate embodied emissions in the PV product trade, lifecycle carbon emissions factors of PV products were obtained from existing lifecycle analysis (LCA) studies for various PV products. Because emissions factors can only be found for a limited number of countries, PV product LCA carbon emissions factors for China [9] were applied to Hong Kong, Taiwan, Russia, India and Turkey; carbon emissions factors for Germany [72] were applied to European countries (with the exception of Norway, whose emissions factor was adjusted according to its energy mix), New Zealand and Brazil; carbon emissions factors for the USA [73] were applied to all American countries, including Canada and Mexico; those for Korea [74] were also applied to Japan and Oceania; those for Singapore [75] were applied to all ASEAN countries. The average values from the above five countries were applied to ROW. Since the PV product trade values in the constructed TFM are US$ values but not in trade volumes, the emissions coefficients were converted into emissions per US$. The Wind database [76] was used to obtain the international average prices of PV products in 2014 and 2017. Lifecycle carbon emissions factors for the PV products are listed in Supplementary Note 3 and Supplementary Table 2.

Embodied local pollutants in the PV trade were also calculated and analysed. This study calculated embodied pollutants in the PV product trade, including the air pollutants PM_{10}, NOx and SO_2 and water pollutant (COD). Because most studies on lifecycle PV product pollutant emissions were conducted in China, LCA pollutant coefficients of China [12] were employed to represent those of China, Hong Kong, Taiwan, Japan, and Korea. The Ecoinvent database [73], a widely acknowledged lifecycle inventory database, was used to acquire pollutant emissions coefficients for the other countries and ROW. The lifecycle emissions factors of local pollutants embodied in PV products, including PM_{10}, NOx, SO_2 and COD, are given in Supplementary Note 3 and Supplementary Tables 3 and 4 for 2014 and 2017.

Based on the PV product TFM, embodied carbon and pollutants can be calculated by equation (1) and equation (2).

$$EC_{i,j} = EF_{i,C} \times a_{i,j} \tag{1}$$

$$EP_{i,j} = EF_{i,P} \times a_{i,j} \tag{2}$$

Where $EC_{i,j}$ and $EP_{i,j}$ are the embodied carbon and pollutants, respectively, transferred from country/economy i to country/economy j. $EF_{i,C}$ and $EF_{i,P}$ are the carbon and pollutant emissions coefficients of the PV product, respectively, in country/economy i.

Further, considering both emissions embodied in export and import simultaneously, the balance of emissions embodied in trade (BEET) [77,78] in the global PV product trade can be calculated by equation (3) and equation (4).

$$\mathrm{BEET}_{Ci} = \sum_j EC_{i,j} - \sum_j EC_{j,i} \tag{3}$$

$$\mathrm{BEET}_{Pi} = \sum_j EP_{i,j} - \sum_j EP_{j,i} \tag{4}$$

Where BEET_{Ci} and BEET_{Pi} are the balance of the embodied carbon and pollutant flows, respectively, of country/economy i, which can be used to reflect whether a country/economy i is a net exporter or net importer of GHGs and pollutants in international trade.

Emissions reduction potential generated from traded solar cells and modules

To calculate the emissions reduction potential of traded PV products, several steps are involved. First, trade values of solar cells and modules were converted into trade volumes based on product prices. Second, solar power generation potential was predicted for the installed capacity increment attributed to solar cell and module trade. Third, the lifetime emissions (carbon and pollutants) reduction potential was determined based on the PV power generation potential.

Two scenarios were assumed for the emissions reduction potential estimation. The first scenario was substituting solar power for electricity on the local grid (**SSG**), and the emissions reduction potential was estimated with the average emissions coefficients of the local power grid; the second scenario was substituting solar power for thermal power generation (**SST**) (with the exception of in Australia, whose emissions factors were based on coal-fired power generation), and the emissions reduction potential was estimated with the average emissions factors of local coal-fired power plants or thermal power plants. (Supplementary Data 32-33).

For PV product m, the trade volume of export country i to import country j, $TV_{i,j}$, was calculated by equation (5).

$$TV_{i,j} = a_{i,j} \div P_m \tag{5}$$

Where P_m is the international price of solar cells and modules.

The PV power generation potential in country j resulting from solar cells and modules imported from country i, $QE_{i,j}$, was obtained by equation (6) [79].

$$QE_{i,j} = TV_{i,j} \times \frac{Irra_j}{H_{stc}} \times PR \times SL \times LR \tag{6}$$

$$LR = \sum_{y=1}^{SL} \frac{(100 - 0.7 \times (SL - 1))}{100} \tag{7}$$

Where $Irra_j$ is the annual irradiation (kWh/m^2/year) in country j, and national level data were obtained from IEA [5] and PVGIS database [80]. H_{stc} is the irradiance at standard test conditions, equal to 1 kW/m^2. PR is the performance ratio, which was set to 80%. SL is the PV system lifetime ranging between 20 and 40 years and was set to 30 years here. LR is the coefficient considering the total efficiency loss ratio (0.7% per year) of the PV system. PR, SL and LR were set based on the IEA recommended value [81].

This study defined the emissions reduction factors of CO_2 and pollutants attributed to PV application by equations (8) - (9).

$$ERF_{i,C} = EF_{i,C,LPG} \; or \; EF_{i,C,Ther} \tag{8}$$

$$ERF_{i,P} = EF_{i,P,LPG} \; or \; EF_{i,P,Ther} \tag{9}$$

Where $ERF_{i,C}$ and $ERF_{i,P}$ are the carbon and pollutant emissions reduction factors of PV application, respectively, in country/economy i. $EF_{i,C,LPG}$ and $EF_{i,P,LPG}$ represent the carbon and local pollutant emissions coefficients of the local power grid, respectively, in country/economy i, which were used in the **SSG** scenario. $EF_{i,C,Ther}$ and $EF_{i,P,Ther}$ are the carbon and local pollutant emissions coefficients of local thermal power generation, respectively, which were used in the **SST** scenario.

For the SSG scenario, the $EF_{i,C,LPG}$ factors of EU countries, the USA, Canada, Norway, Turkey, Australia, New Zealand and China were obtained from official statistics [82-90], those of other identified trade partner countries/economies were calculated according to IEA statistics [6,91], and the global average emissions factors of electricity generation obtained from the IEA [92] were applied to ROW. The $EF_{i,P,LPG}$ factors in 2014 and 2017 of EU countries, the USA, Canada, New Zealand, other OECD members, and China were also drawn from official statistics or reports [83,84,86,93-99]. For other countries/economies lacking emissions data, the EDGAR database[100] was used to acquire 2012 emissions data, which were extrapolated to 2014 and 2017 according to changes in their electric power structure [6]. The average $EF_{i,P,LPG}$ value was used to represent ROW.

For the SST scenario, the $EF_{i,C,Ther}$ and $EF_{i,P,Ther}$ of the USA, Canada, Australia, EU countries, Norway, Turkey, other OECD members and China were obtained from official statistics [6,83-86,88,89,93-99,101-104], coal-fired power generation data were obtained for Australia, and thermal power generation data were obtained for the remaining economies. For other countries/economies whose thermal power generation information could not be directly obtained, we estimated their $EF_{i,C,Ther}$ and $EF_{i,P,Ther}$ based on the EDGAR database [105] and local electricity structure [6], and the change rates were estimated as in the SSG scenario [106,107].

The quantity of the emissions reduction in terms of CO_2 and pollutants was calculated by equations (10) - (11).

$$QER_{i,j,C} = QE_{i,j} \times ERF_{j,C} \tag{10}$$

$$QER_{i,j,P} = QE_{i,j} \times ERF_{j,P} \tag{11}$$

Where $QER_{i,j,C}$ and $QER_{i,j,P}$ are the carbon emissions and local pollutant reduction potential of the application of solar cells and modules, respectively, exported from country/economy i to j and generating power in j.

Computable partial equilibrium model (CPE) to evaluate extra tariff impacts on the PV trade

According to the WTO [108] and MOFCOM [109], countries/economies, such as Brazil, Mexico and some ASEAN countries, impose tariffs on PV products. Trade barriers such as antidumping or countervailing continually influence global PV product trade, production and application [5]. Several major PV product trade conflicts occurred in 2017; for example, the USA complained that the domestic PV industry was damaged by imported products and vowed to impose additional tariffs on imported solar cells and modules, which led to objections from China, Korea, and Mexico. Europe restricted the minimum import price (MIP) and maximum shipping volume of Chinese PV products. Turkey and India also imposed tariffs on imported solar modules from China [5]. On April 16, 2020, the USTR removed the Section 201 tariff exclusion for the bifacial solar module [33].

This study adopted a global simulation model (GSIM), which is a multiregional computable partial equilibrium model (CPE), to simulate the impact of tariff imposition on global solar cell and module trade and production, solar power generation and the corresponding emissions reduction potential. The GSIM model was developed and expanded by Francois and Hall [110] and focuses on industry analysis from a global perspective, allowing for rapid and relatively transparent analysis of commercial policy issues with minimal data and computational requirements.[48,111-113]

The GSIM model can incorporate a maximum of 25 countries/economies or trade partners, so the 24 largest PV product trade partners and ROW_{CPE} (composed of the countries/economies other than the largest 24) were included. Solar cells and modules, as the major traded PV products and key objectives of trade conflicts, were taken to carry out the simulations. Two trade policy scenarios were assumed. The business-as-usual (BAU) scenario was set according to actual tariffs imposed on global traded solar cells and modules in 2017. In the BAU scenario, the USA, European countries, Canada, and Turkey impose tariffs on imported Chinese solar cells and modules, and Brazil and Mexico impose tariffs on imported solar cells and modules from all other economies. The trade barrier scenario (TBS) or extra tariff imposition scenario, was a tariff-intensified scenario: based on recent business reports, the worst situation of the multilateral trade tariff imposition proposition can involve that, European countries reinstate tariff on Chinese PV product and expand to solar cells and modules from all origins; Brazil and Mexico keep tariff on solar cells and modules from all origins; India impose tariffs on imported solar cells and modules from all origins; Canada and Turkey keep imposing tariffs on Chinese solar cells and modules; and the USA impose 201 tariff on Chinese solar cells and modules and expand to those from all origins, and China imposes retaliation tariffs on the USA solar cells and modules. For TBS, the import tariff rate of the EU was set to 47.6% based on the European Commission determination [114,115]. The import tariff rate of the USA was set to 30% based on Section 201 [116], while a higher rate was imposed on Chinese PV products considering the superposition of Section 201, Section 301, and antidumping and countervailing policies [116-118]. The other tariff rates were set based on the WTO [108], MOFCOM [109], official statistics [119] or business news reports [120,121].

In terms of trade statistics, the top 24 PV product trade countries/economies in 2017 were selected, and the other countries/economies were merged into ROW_{CPE} (Supplementary Table 5). Three groups of data were collected and input into the GSIM model: trade value among the selected countries/economies, elasticities (supply, demand and substitution elasticities of solar cells and modules), and tariff rates before and after trade measure implementation. Trade values were obtained from UN Comtrade [52], tariff rates were obtained from the WTO [108] and MOFCOM [109] (Supplementary Data 34), and elasticities of solar cell and module trade were obtained from current research [48] (Supplementary Table 6). The output value of the solar PV industry is quite limited, and the solar cell and module output values of various countries/economies in this study were calculated by the authors based on local production (or capacity) and price statistics. Domestic sales were obtained by deducting export values from output values. Detailed data sets and selected economies are shown in Supplementary Note 4.

Projection to the PV development scenario

Traded solar modules accounted for over 100% in 2014 and 76.89% in 2017 of the global newly installed solar power capacity. Based on the latest IEA forecast, the cumulative installed PV power generation capacity will surge to 3,142 GW in 2040 [122], which is almost 8 times larger than that in 2017. IRENA predicts that annual PV installation in 2030, 2040 and 2050 will reach 300, 355 and 360 GW [50].

Based on the IRENA prediction, this study assumed that (1) solar module retirement would begin in 2040 (global PV capacity installed before 2010 would retire in 2040), (2) global PV trade pattern would keep stable, (3) the change rate of PV module trade volume would be the same as that of newly installed PV capacity between 2017-2050 in BAU, (4) installation of traded PV modules before 2017 were ignored to simplify calculation. Newly installed global PV capacity in year y ($GNI_{PV,BAU,y}$) and newly installed capacity of traded PV ($GNI_{PVTR,BAU,y}$) in the BAU scenario were calculated by interpolation.

In TBS, global PV module output decrease (OD_{PV}) and traded PV cells and modules decrease (TD_{PV}) based on the 2017 baseline from the tariff were obtained by the GSIM model. The decrease rate of newly installed PV capacity (DNI_{PV}) and decrease rate of newly installed traded PV capacity (DNI_{PVTR}) were calculated by equations (12)-(13). These rates were adopted to estimate tariff impacts on global PV application by 2050 and used to obtain global newly installed PV capacity ($GNI_{PV,TBS,y}$) and newly installed traded PV capacity in year y ($GNI_{PVTR,TBS,y}$) under TBS with equations (14)-(15). Global cumulative PV capacity installation in year y ($GCI_{PV,y}$) and cumulative traded PV capacity installation in year y ($GCI_{PVTR,y}$) under the BAU and TBS scenarios were calculated with equations (16)-(17) with annual retirements of total PV capacity installation ($GRI_{PV,y}$) and traded PV capacity installation ($GRI_{PVTR,y}$) considered. [7,123-125]

$$DNI_{PV} = OD_{PV} \div GNI_{PV,BAU,2017} \tag{12}$$

$$DNI_{PVTR} = TD_{PV} \div GNI_{PVTR,BAU,2017} \tag{13}$$

$$GNI_{PV,TBS,y} = GNI_{PV,BAU,y} \times (1 - DNI_{PV}) \tag{14}$$

$$GNI_{PVTR,TBS,y} = GNI_{PVTR,BAU,y} \times (1 - DNI_{PVTR}) \tag{15}$$

$$GCI_{PV,y} = \sum_{y}(GNI_{PV,y} - GRI_{PV,y}) \tag{16}$$

$$GCI_{PV,y} = \sum_y (GNI_{PV,y} - GRI_{PV,y}) \quad (17)$$

Based on the above indicators, tariff impacts on solar PV power generation and emissions reduction potential were calculated with the same method as counting “emissions reduction potential generated from traded solar cells and modules”.

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Competing interests

The authors declare no competing interests.

Figures

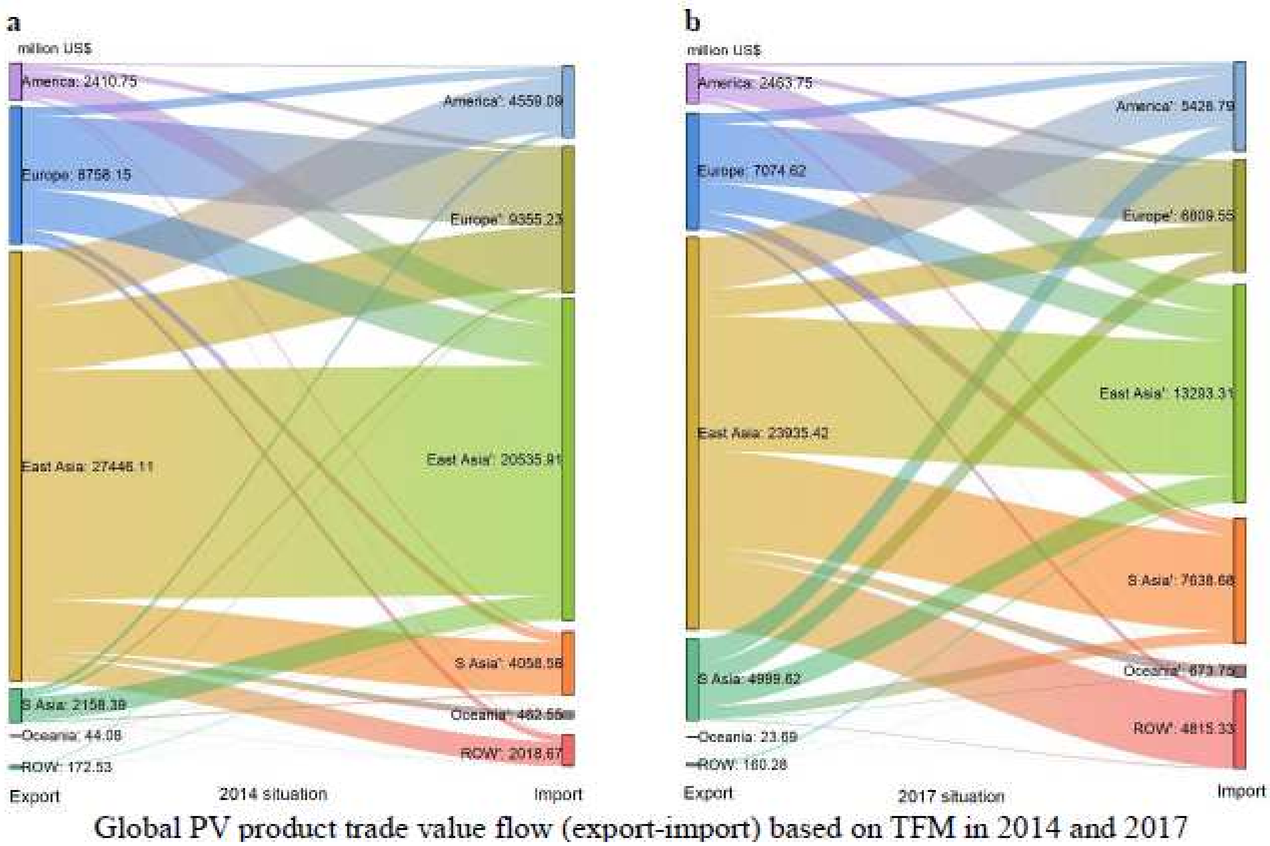

Figure 1

Global PV installation and PV product trade flow. Sankey diagrams present global PV product trade flows in 2014 and 2017. Southeast Asia and other Asian countries is abbreviated as "S Asia". a This figure shows global PV trade flows in 2014. East Asia and Europe were the most important PV product exporters and importers. The top 3 biggest extra-region flows were from East Asia to Europe, then to America and to Southeast Asia and other Asian countries. b This figure shows global PV trade flows in 2017. East Asia was still the biggest PV product exporter and importer, and Southeast Asia and other Asian countries became the second largest importer. The top 3 biggest extra-region flows were from East Asia to Southeast Asia and other Asian countries, then to America and to Europe. From 2014 to 2017, the global PV trade flow pattern became more diversified and evenly distributed. East Asia maintained a leading role in the global PV product trade, especially China, which was the key PV product production and trade hub. Europe and America tended to produce and export silicon to and import solar cells and modules from Asia. Southeast Asia and other Asian countries increased their share in the global PV product market and intensified trade links with other regions, owing to local cheaper labour and land costs, lower tax rates, and less strict environmental regulation 30. Import value gaps between East Asia and other regions narrowed (see Supplementary Data 5-10 for more details). This study converted all the currencies to US dollars first and then converted them to 2010 US$ for comparability.

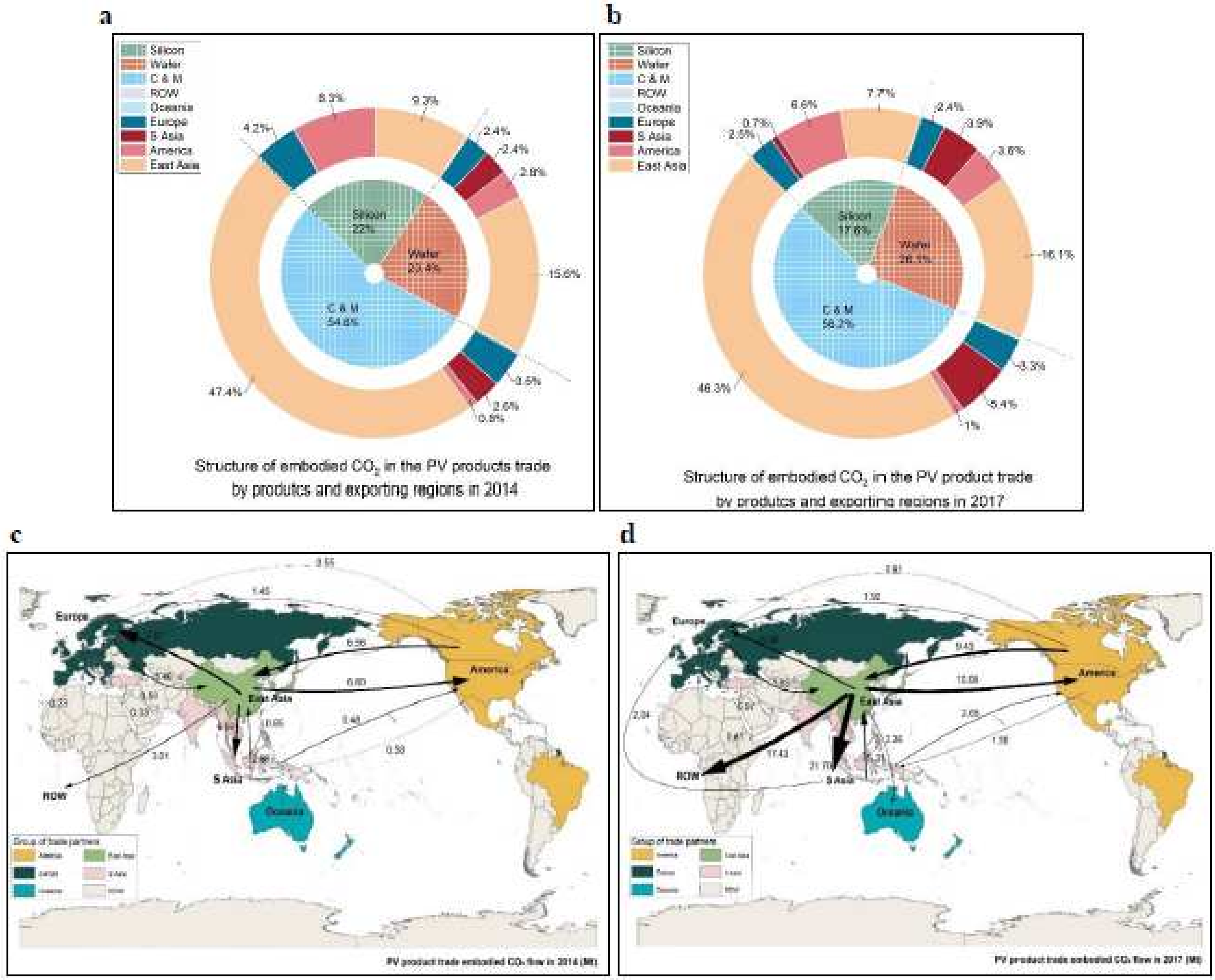

Figure 2

Structure and flow of CO2 embodied in the global PV product trade (2014 and 2017). These maps represent CO2 embodied in the global PV product trade in 2014 and 2017. a, b In the two sub-figures, inner pies represent the proportion of carbon embodied in different PV product exports; outer doughnuts explain the proportion of embodied carbon contributed by each exporting region. c, d The two sub-figures represent flow of carbon embodied in PV product trade between regions in 2014 and 2017. From 2014 to 2017, noticeable growth in embodied carbon appeared in addition to an increase in PV product trade, especially in East Asia, Southeast Asia and other Asian countries. Compared with in 2014, in 2017, carbon emissions embodied in PV product trade increased by 61.76% or 46.49 MtCO2e. East Asia observed the largest increase in embodied carbon exports (30.87 MtCO2e), which increased by 56.68%, and its trade with Southeast Asia and other Asian countries contributed 15.11 MtCO2e to this increase. Southeast and other Asian countries had the second highest growth of embodied carbon exports at 8.32 MtCO2e and the largest increase rate at 216.79%. China accounted for the largest increment (20.65 MtCO2e), followed by the USA (3.99 MtCO2e) and Taiwan (3.84 MtCO2e). The increase in Southeast Asian countries was conspicuous, e.g., Malaysia (3.10 MtCO2e) and Vietnam (1.80 MtCO2e). For embodied carbon imports, growth in Southeast Asia and other Asian countries was the largest (17.85

MtCO2e), followed by that in America (6.54 MtCO2e), and the leading countries were India, China and the USA (see Supplementary Data 11-12). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

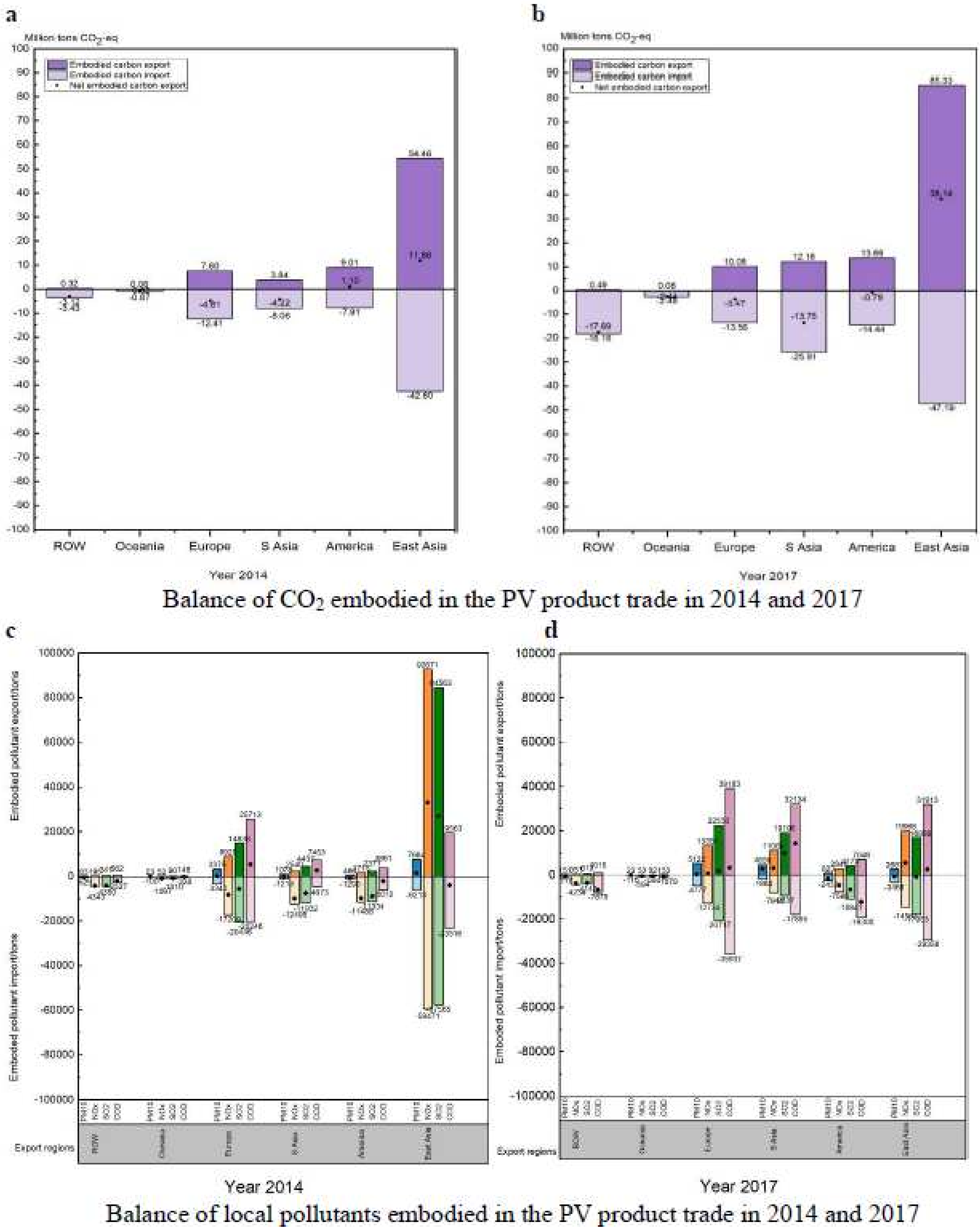

Figure 3

Balance of CO2 and local pollutants embodied in the PV product trade in 2014 and 2017. These column charts show the balance of total CO2 and pollutants embodied in the global PV product trade by region, bars above the horizontal axis (y=0) represent CO2 and local pollutants embodied in exports, and bars under the horizontal axis represent CO2 and local pollutants embodied in imports. a, b Black dots represent the balance of embodied CO2 (BEET□). c, d Black dots display the balance of embodied local pollutants (BEET□).

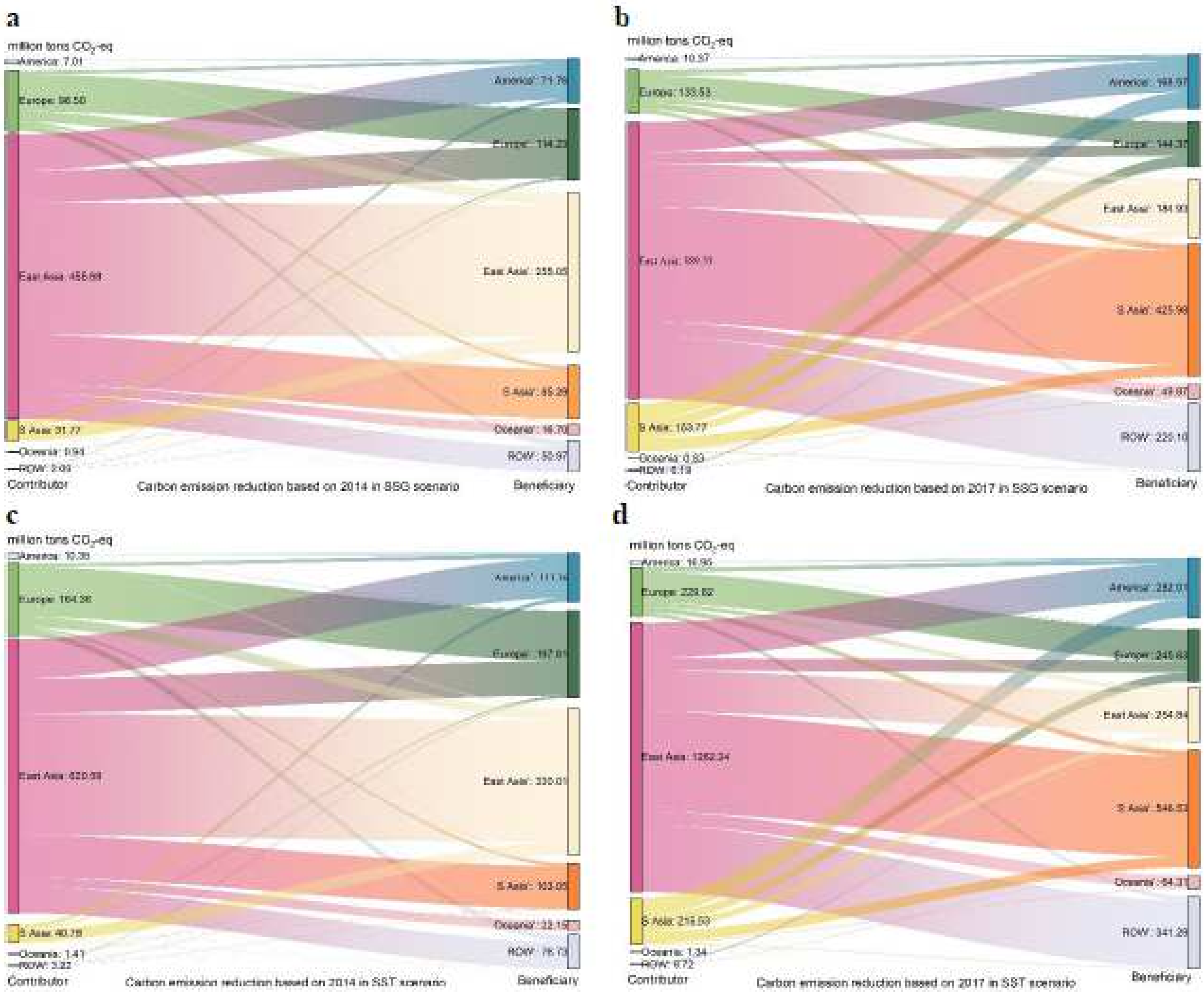

Figure 4

Carbon emissions reduction potential of traded solar cells and modules in 2014 and 2017 (30-year lifetime; SSG and SST scenarios). a, b, c, d The Sankey diagrams show the CO2 emissions reduction potential transferred from exporter regions (right) to importer regions (left) in 2014 and 2017 under SSG and SST scenarios.

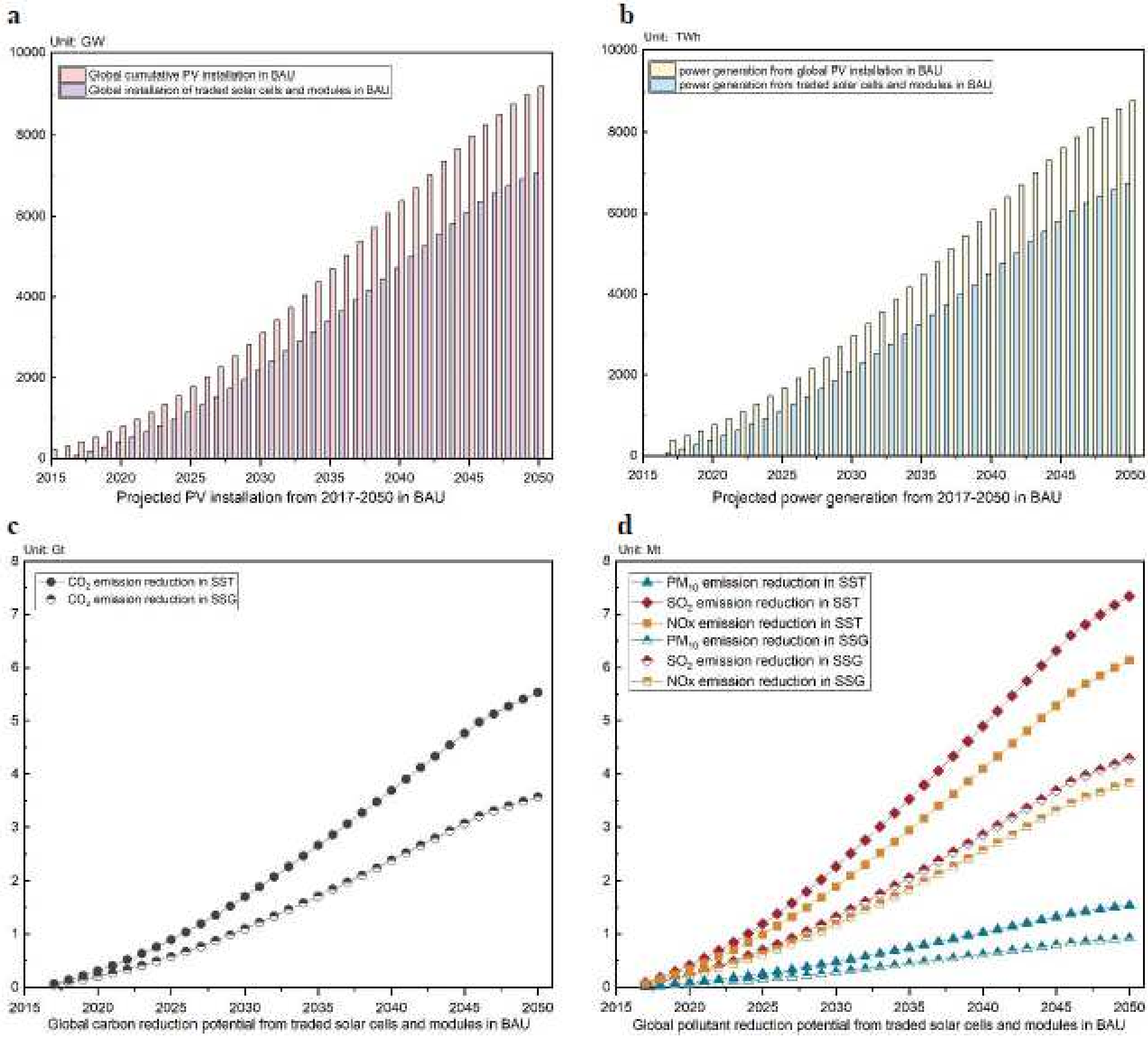

Figure 5

Global carbon and pollutant reduction potential from traded solar cells and modules in BAU. a Column chart shows projected global cumulative PV installation and traded PV capacity in the BAU scenario. Global cumulative installed PV capacity values from 2015-2017 were drawn from IEA-PVPS5,7, and the capacity values from 2017-2050 were projected by the authors based on IRENA50 (see methods for details). b Column chart shows projected power generation potential from globally cumulative PV installation and traded PV capacity in the BAU scenario. c, d These two figures show carbon and pollutant emission reduction potential from traded solar cells and modules from 2017-2050 in BAU.

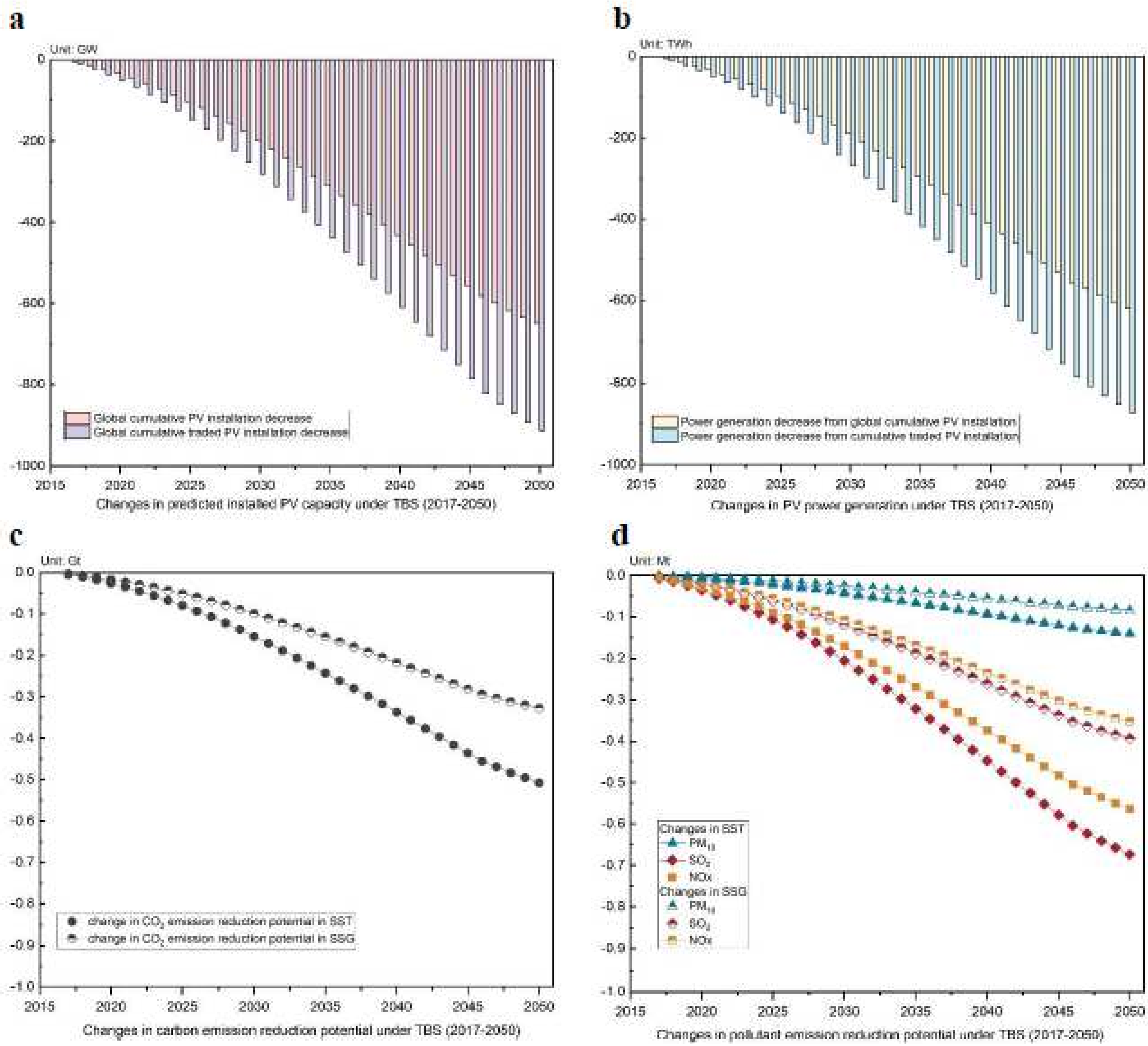

Figure 6

Extra tariff impacts on the global PV capacity installation, PV power generation and emissions reduction potential (2017-2050) under trade barrier scenario (TBS). a, b Column charts show decrease of global cumulative PV capacity installation, traded PV capacity and the decrease of global PV power generation in TBS to represent the impacts of extra tariffs on PV product trade. c, d The point-line charts show the decreases in CO2 and air pollutant emissions reduction potential in the SSG and SST scenarios due to the impacts of extra tariffs on PV product trade.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- PVXXtradebarrierandenvironmenXXSI2020.9.10.pdf
- PVtradebarrierandenvironmentSIdata2020.9.2.xlsx