Low carbon transition of global power sector may enhance sustainable development goals

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Article

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Abstract

Low-carbon power transition, key to combatting climate change, brings far-reaching effects on achieving Sustainable Development Goals (SDGs), in terms of resources use, environmental emissions, employment, and many more. Here we assess the potential impacts of power transition on multiple SDGs progress across 49 economies under six socio-economic-climate scenarios. We find that the low carbon power transition under Representative Concentration Pathway (RCP) 2.6 scenarios could lead to approximately 10% improvement in global SDG index score from 65.30 in 2015 to 71.62–71.64 in 2050. However, the improvement would be significantly decreased to 1.91%-4.98% and 3.42%-5.24% under RCP6.0 and RCP4.5 scenarios, respectively. Power transition could improve the overall SDG index in most developed economies under all scenarios while undermine their resources-related SDG scores. The power transition induced changes in international trade would improve developed economies' SDG progress, but jeopardize that of developing economies which usually serve as resource hubs to meet the demand for low carbon power transition in developed economies.

Introduction

The current fossil fuel-dominated power sector contributes for near 40% of global annual energy-related CO_2 emissions [1,2]. The low carbon transition of the power sector is crucial to tackling climate change and ensuring the future supply of energy [3,4]. According to the International Energy Agency (IEA), the climate target in the Paris Agreement that pursuing efforts to limit end-of-century warming to 1.5°C, cannot be achieved until the share of energy production from low-carbon energy technologies rising to 85% by 2040 [1].

However, the impacts of power sector transition are beyond climate. It brings far-reaching effects on achieving Sustainable Development Goals (SDGs) [5], in terms of resources use[6,7], environmental emissions [4], employment [8], and many more[9,10]. However, power transition may ease one problem while exacerbate others at the same time. For instance, the closure of coal-fired power plants will reduce cooling water withdrawal (advancing SDG 6: Clean Water and Sanitation) [11,12], but cause massive job losses in coal power industry and its various ancillary, upstream, and downstream industries (hindering SDG 8: Decent Work and Economic Growth) [13,14]. Expansion of low-carbon power such as wind power and solar energy as substitutes for fossil fuels can improve countries' ability to deal with climate change (advancing SDG 13: Climate Action) [15], while increases demand for critical materials (hindering SDG 12: Responsible Consumption and Production) [16,17]. Thus, there is a need to understanding the impacts of power transition on global SDG progress from multiple aspects.

Previous studies have primarily focused on the impacts of specific national or regional power sector transition on a single aspect of sustainable development, such as regional employment [18], economic growth [19], natural resources use [20,21], greenhouse gas and pollutant emissions [22]. However, few have evaluated the environmental–social–economic interrelationships (trade-offs or synergies) of the power sector transition and its impacts on each region toward achieving the multiple SDGs simultaneously. The lack of comprehensive assessment may lead to unintended consequences, or even hinder some SDGs progress, when designing power transition pathways. For instance, Wang et al. found that Developing Asia's long-term power plan featuring coal power generation has not yet included the impact on regional sustainable use of water resources, which may exacerbate its water shortage (hindering SDG 6: Clean Water and Sanitation), if without any strategies to reduce cooling water use [23]. Additionally, power transition in one region affects not only the local SDGs, but also SDGs progress in other regions via inter-regional trade. The expansion of renewable power or the reduction of fossil fuels in electricity mix in one country might lead to the changes of environmental emissions, resources consumption and employment embodied in products and services from global supply chains, thus potentially influencing other regions' SDGs [24]. Some researchers have conducted initial investigations and found out that European renewable energy directive will harm forests of tropical countries, such as Indonesia and Brazil, through wood trade (hindering SDG 12: Responsible Consumption and Production) [25]. Thus, there is a need to explore the role of international trade in regional SDG progress for preventing the power transition at the expense of SDG in other regions.

By applying Global Change Assessment Model (GCAM) [26], Multiregional Input-Output Analysis (MRIO) [27,28] and SDG assessment approach [29], here, we examine the direct and supply-chain effects of power transitions throughout the world on regional and global SDGs, including the net environmental and socio-economic changes under six combination scenarios between the Shared Socioeconomic Pathways (SSP2 and SSP1) [30] and Representative Concentration Pathways (RCP6.0, RCP4.5 and RCP2.6) [31] (**see detailed explanations in Methods**). Our findings demonstrate that low carbon transition of global power sector could enhance the overall SDG performance with huge regional disparities on individual target of the SDGs.

Results

The environmental and socio-economic impacts of global power sector transition

Figure 1 shows the net changes of environmental emissions, water resources use, material use, and socioeconomic impacts (the basic indicators to evaluate SDG progress) associated with global power transition under six different scenarios- SSP2 + RCP6.0, SSP2 + RCP4.5, SSP2 + RCP2.6, SSP1 + RCP6.0, SSP1 + RCP4.5 and SSP1 + RCP2.6.

We find that global CO_2 emissions (34.85 Gt in 2015) would increase by 5.86–13.68% and 4.94–8.94% under RCP6.0 and RCP4.5 scenarios between 2015 and 2050, but decrease by 6.79–9.87% under RCP2.6 scenarios (Figs. 1a and 1b). The discrepancy of emissions under different scenarios are mainly based on the assumptions of different energy mix of electricity production (**Table S1**). Given the stronger pollution controls in the future [32,33], all the projections show decreasing trends of PM emissions (Figs. 1c and 1d).

For blue water consumption, our scenario analysis shows a similar trend as the changes in CO_2 emissions, except the SSP1 + RCP2.6 scenario results where a significant annual decrease of 3.25 Gm^3 (-0.28%) blue water consumption associated with power transition by 2050 could be observed, in contrast with the increase of blue water consumption under the RCP4.5 and RCP2.6 scenarios (Figs. 1e and 1f). However, blue water withdrawal would gradually decrease under all scenarios due to the extensive application of circulating cooling technology (Figs. 1g and 1h).

Along with higher demand for electricity in the future, all scenarios are accompanied with an increasing use of materials, such as metal, non-metal minerals and biomass for power transition, except a decrease of fossil fuels (Figs. 1i-l). However, power sector would consume much less fossil fuel materials and more metal, non-metal minerals and biomass materials under the RCP2.6 scenarios, compared with the results under other scenarios.

In terms of socio-economic impacts of the power production and transition, we could see a significant increase in employment (Figs. 1m and 1n) under all scenarios, due to the high future demand of electricity. As per unit of installed capacity for renewables can generate more jobs than that of coal power [34], our results show that power generation and transition under the RCP2.6 scenarios (the most ambitious scenario with renewables generation) may bring more job opportunities, compared with the results under RCP6.0 and RCP4.5 scenarios.

Power transition’s impacts on global SDGs

Here, we translate the changes in environmental and social-economic indicators into global SDGs progress using the United Nations SDG assessment approach (**see method section**). Our results show that the global SDG index score, defined as the overall performance in achieving all individual SDG evaluated, would increase from 65.30 in 2015 to 71.62–71.64 in 2050 under RCP2.6 scenarios, compared with 66.55–68.55 and 67.53–68.72 under RCP6.0 and RCP4.5 scenarios, respectively (Fig. 2a). Advances in technology and efficiency in electricity generation play a dominant role in global SDG performance of the power sector. We also find that global SDG index scores would rise even when fossil power generation increases under the RCP6.0 and RCP2.6 scenarios.

Almost all individual SDG would benefit from the transition at global scale. In 2050, SDG 6.4, SDG7.2, SDG 8.4, SDG 8.5, SDG 11.6, and SDG 12.2 present higher scores under RCP2.6 scenarios than that under RCP4.5 and RCP6.0 scenarios. The resources use and socio-economic benefits from the low carbon transition are intrinsically related to the reduction in blue water use, fossil fuels use from the shutdown of a large number of thermal power plants. However, before 2035, the continuous expansion of the scale of electricity generation would lead to a large amount of CO_2 emissions in both power generation and its upstream supply chains (e.g., manufacturing sector), which lead to a decline in the scores of SDG 9.4 and SDG 13.2. For example, in 2035, SDG 9.4 score under SSP2 + RCP2.6 (50.43) is less than 9.07% of that in 2015 (55.46).

The impacts of power transition on regional SDGs

The changes of SDG index score vary significantly across economies (**Figure. 3**). Here, we take SSP2 as an example. In general, the higher the GDP per capita is, the more inclined an economy is to improve the SDG index scores and vice versa (**Table S2**). During the period of 2015–2050, the average SDG index scores of developed economies would increase by 3.70% and the power transition in almost every developed economy would improve their SDG scores to some extent under RCP2.6 scenario. However, a few developed economies, such as Canada, may face a decline in their SDG scores under the RCP6.0 scenario. In contrast, more than half of the developing economies, mainly from Asia and Africa, would have a decline in their SDG scores under the RCP6.0 scenario, while this number decreased to about 20% under the RCP2.6 scenario.

Estonia, one of the countries that completely relies on fossil fuel for power generation, would experience the biggest increase in SDG index score by 2050 under all scenarios, with a range of 3.05 to 12.36, due to significantly expansion of renewable power for substitution of coal power under the European Climate Law [35]. This verifies that strict climate legislation can effectively improve the sustainable development level of regions that are highly dependent on fossil power. In contrast, Indonesia has the biggest drops in SDG index score by 6.79, because natural gas power would grow substantially in this emerging economy.

Regional power transition could also lead to synergies and trade-offs between different individual SDGs under RCP2.6 (Fig. 4c). As for synergies, more than 60%, 90%, 80%, 80%, and 80% of the economies considered would have an increase in SDG 6.4 scores, SDG 8.5 scores, SDG 9.4 scores, SDG 11.6 scores, SDG 13.2 scores. However, there exists differences between SDG 8.4/12.2 and SDG index. For example, under RCP2.6, United States' SDG index score would increase by 7.78 in 2050, but due to the increase of material use during the transition, its SDG 8.4 score fall by 0.53. In addition, the power transition will improve all individual SDGs score in some economies, such as Bulgaria, China, Australia.

The effects of power transition related international trade changes on SDGs

Power transition will not only change the scale and patterns of international trade, but also exert effects on environmental emissions, resources consumption and employment embodied in exports and imports, thus influencing SDG performance in different regions. The energy transition induced international trade change would improve the overall SDG performance (2.33–4.36%) globally between 2015 and 2050 (Fig. 5a). However, the overall impact is rather limited, as the amount of traded commodities and services (measured by monetary value) related to power sector only account for less than 2% of the international trade. Climate-related SDG (SDG 13.2) performance will have the highest degree of improvement (0.5%), mainly due to the reduction of CO_2 emissions embodied in thermal power-related trade, under RCP2.6. (Fig. 5h). The employment-related SDG (SDG 8.5) performance will be improved, mainly because of the expansion of labor intensive renewable power sectors (Fig. 5d). However, all scenarios show a decline (0.03–0.13%) in the average scores of material use-related SDGs (SDGs 8.4 and 12.2), due to the increase in power production related resource use met by international trade (Figs. 5b, 5c and 5g).

From a regional perspective, more than 70% of economies would improve their SDG performance under all scenarios (Fig. 5). Only the SDG performance of developing economies with rich fossil energy and material resources, such as the Middle East, would be impeded by international trade, as the expansion of power production results in the increase of power sector related resource consumption and environmental emissions embodied in international trade.

Discussion

For the first time, this study performs a quantitative analysis on the impacts of power sector transition with regard to global and regional multiple SDGs performances. We find that an improvement of global SDG index scores (the average score of eight selected SDGs) during 2015–2050 under all six combination scenarios. Power transition brings an increase of 1.91–4.98%, 3.42–5.24%, and 9.67–9.71% in global SDG index score under the RCP6.0, RCP4.5 and RCP2.6 scenarios, respectively. However, the change of regional individual SDG score isn't always consistent with the change of average SDG index score. For instance, resource-related SDGs (SDGs 8.4 and 12.2) scores on 30 of the 49 economies, on the contrary, will become worse if the currently fossil-dominated power structure transited to a renewable-dominated one (SSP2 + RCP2.6).

According to Sustainable Development Report 2020, the progress of achieving the SDGs by 2030 lags far behind the schedule predesigned by the UN [29]. One of the main reasons is that there is a lack of understanding of the interactions between SDGs, which is essential to trade-offs between SDGs and advance the overall SDGs with minimal efforts[10,36]. As our research reveals the SDGs synergies and trade-offs in global and regional power transition, which provide an insight into advancing the power transformation and improving the current SDG "dilemma".

Boosting developing economies lagging carbon power transition is crucial

Our results demonstrate that whether the global SDG performance can be improved will be determined by developing economies' power transition. The main reason is that fossil power contributed more than 70% of the electricity demand in developing economies. As a result of gradual expansion in population and economy, the electricity demand of developing economies will increase by 81.6-112.3% between 2015 and 2050, which is much higher than that of the developed economies (23.2–28.4%). If power generation in developing economies is still dominated by fossil fuels, there will be a large amount of greenhouse gas and pollutant emissions, as well as a large amount of water resources and fossil fuels and minerals depletion, thus posing great threats to global SDG progress.

To promote the clean and low carbon power transition in developing economies is crucial to global SDG progress. Meanwhile, due to the different levels of economic development and power structure, different developing economies need to take varying measures.

For Africa, the continent with the lowest average income, the biggest challenge facing transition is the lack of sufficient financial support [37]. For example, African low-carbon electricity transition cannot be achieved until investments in power growing by two-and-a-half times through to 2040, according to IEA. Given the limited financial capacity and financial constraints of utilities of governments, private sources of finance will be critical to bridge investment gaps. However, more than 1/3 of sub-Saharan African countries such as Nigeria, Sudan do not allow for private sector participation in electricity generation or networks, which greatly jeopardizes the decarbonization of electricity in these areas [1]. For the smooth transition of the region, private investment can be appropriately introduced.

For China and India, the two biggest coal-fired power producers in the world, a rapid transition away from unabated coal use is essential. Recent regional trends reflect a shift in coal power prioritization from the US and EU to many fast-developing countries in Asia, especial in China and India [38]. Thus, specific policy efforts that target coal-power production reduction are critical, for example, reductions in multilateral development banks' financing of coal projects, national limits on coal consumption. More importantly, the state needs to improve its commitment. China has come up with clear carbon neutral targets and India needs to catch up.

Measures to coordinate power transition and SDGs

Transforming the power sector to low-carbon energy under the RCP2.6 (or rapid low-carbon power transition) is verified that it can bring huge co-benefits to global SDGs performance on the whole. However, the situation in each region differs from one another. All individual SDGs in some economies such as Germany, Spain, can be advanced by rapid low-carbon power transition. This indicates that the current and stated transition strategies of these countries are relatively sustainable. However, it is worth noting that the power transition may lead to local SDG conflicts in these economies. For example, the Indian government's clean energy transition strategies (solar capacity addition targets are accompanied by the retirement of thermal capacity) will create job opportunities primarily (60% of total) located in western and southern parts of India (advancing SDG 8.5:Achieve full and productive employment), while leading to job losses being concentrated in the coal-mining states located in eastern India (hindering SDG 8.5) [39]. Thus, it is recommended a comprehensive review of the cross-regional impact of the power transition in large economies, such as the United States and India, to reduce regional imbalances from transition. Meanwhile, specific development plans for sub-regional low-carbon power transition are needed.

For most countries, the rapid low-carbon transition may cause conflicts between individual SDGs progress (where progress in one goal hinders progress in another), which may need great attentions. For example, the expansions of wind power and PV in the United States will increase demand for metals and nonmetals, and undermine its SDG 8.4. In response to the material requirement or bottleneck for the future deployment of low-carbon power technologies, it is critical to increasing secondary supply of materials (recycle) instead of expanding mineral exploitation. Given the low rate of recycling of materials and high recycling costs in power sector [7], more efforts need to be exerted into the centralized recovery of retired electrical equipment and the development of technologies with lower costs and higher recovery rates.

Our results also indicate that international trade associated with the low carbon transition of power sector has limited effect on the average SDG performance at global scale, but it may profoundly affect the SDG process of individual countries. This means cross-national inequities in SDGs progress may be exacerbated due to the expansion of renewable power or the reduction of fossil fuels in the electricity mix. For example, under SSP2 + RCP2.6 scenario, by 2050, 42.13% of metal use increases (hindering SDG 8.4 and 12.2) in the RoW America are caused by power transition in the country itself, and the remaining 57.87% are driven by the ripple effects of low-carbon transition in other countries (advancing SDG 9.4 and 13.2) through the through global supply chains. This emphasizes global systemic effects of power transition which calls for supply chain management when formulating power transition strategies to facilitate best practice in minimizing impacts on SDG.

Methods

In this study, an integrated assessment framework is applied to assess the potential impacts of power transition on global 49 regional multiple SDGs progress (**Figure S1**). Firstly, prediction of power generation and power mix by region under SSP + RCP scenarios are obtained from the Global Change Assessment Model (GCAM). Then, the environmental and socio-economic impacts of global and regional power sector transition under each scenario are quantified by the Multiregional Input-Output Analysis (MRIO) approach. Finally, the changes in environmental and social-economic indicators are translated into SDGs progress using the United Nations SDG assessment approach.

Scenarios of future power generation by region and technology. We derive future power generation under a range of climate mitigation scenarios from the GCAM. GCAM is a global model that simulates the behavior of, and interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate, which has been widely used to produce scenarios for international and national assessments [26]. In this study, six scenarios are selected across two aspects to analyze future global power generation by region and technology according to the Intergovernmental Panel Climate Change (IPCC) reports [40]. One aspect is the Shared Socioeconomic Pathways (SSPs) [30], which were developed along the dimensions of challenges to mitigation and to adaptation climate change and can sufficiently cover the relevant socio-economic dimensions. The other aspect is the Representative Concentration Pathways (RCPs) [31], which represent the ambition of climate policies. Each SSP + RCP combination represents an integrated scenario of future climate and societal change, which can be used to investigate the global and regional power transition effort required to achieve that particular climate outcome. To compare the impacts of different degrees of power transition, we combine moderate SSP narrative (SSP2) and sustainable SSP narrative (SSP1) with three levels of RCP scenarios (6.0, 4.5 and 2.6 Wm^{-2}), respectively. In detail, the GCAM model directly provides the regional (32 regions globally), renewable, fossil fuel-and with/without CCS-specific power generation every 5 year from 2015 to 2050.

Quantifying the environmental and socio-economic impacts of power transition. The Multiregional Input-Output Analysis (MRIO) model are used to quantify the environmental and socio-economic impacts of power transition. This model captures both direct and indirect effects of ten power production sub-sectors (including coal power, gas power, nuclear power, hydroelectricity, wind power, petroleum and other oil derivatives power, biomass and waste power, solar photovoltaic, solar thermal, and geothermal power) on environmental emissions, water resources use, material use and employment. The basic framework of MRIO is as follow:

$$\mathrm{X} = (I - A)^{-1} F$$

1

where$\mathrm{X} = \left[X_i^r\right]_{n\times 1}$,$X_i^r$ is the total output of *i*th sector in region *r*. *I* is the identity matrix. $\mathrm{A} = \left[A_{ij}^{rs}\right]_{n\times n}$ is the technical coefficient matrix,$A_{ij}^{rs}$is given by $A_{ij}^{rs} = Z_{ij}^{rs} / X_j^s$, in which Z_{ij}^{rs}represents the monetary value flows from *i*th sector in region *r* to *j*th sector in region s andX_j^s is the total output of *j*th sector in region *s*.$(I - A)^{-1}$ is the Leontief inverted matrix (L). F is a column vector of the row sums of matrix $\mathrm{Y} = \left[Y_i^{rs}\right]_{n\times m}$, which is the final demand matrix and Y_i^{rs}represents the final demand of region *s* for the goods and services of *i*th sector from region *r*.

Direct environmental and socio-economic impacts of power production sub-sectors can be calculated using following equation:

$$D_k^t = E_k^t * G_k^t$$

2

Where D_k^t is the direct impacts (environmental emissions, water resources use, material use, or employment) of power production sub-sector k in year t,E_k^t is the direct impacts per unit of power production sub-sector k in year t and G_k^t is the power production of sub-sector k in year t. In addition, we assume that the direct impacts change proportionately to electricity production G_k and the direct impacts intensity E_k between the modelled year (t+1) and the previous year considered in the analysis t, given by the scenarios.

$$D_k^{t+1} = \left(E_k^{t+1} / E_k^t\right) * \left(G_k^{t+1} / G_k^t\right) \times D_k^t$$

3

The indirect environmental and socio-economic impacts of power production sub-sectors are evaluated based the intermediate inputs from other sectors into the power sectors using following equation:

$$R_t = \hat{f_t} L_t \hat{X'}_t$$

4

Where R_t is the direct impacts of power production sub-sectors in year t, f_t is a vector of the direct impact intensity (the direct impact per unit total output from each sector) for all economic sectors in all regions in year t, L_t is the Leontief inverted matrix in year t. Since we only need the output of power production sub-sectors, we create column vector $X^{'}$, composed of zeros and X_i^r at the appropriate positions for power production sub-sectors. In addition, we also assume that the indirect impacts change proportionately to electricity production G and the direct impacts intensity f between the modelled year (t+1) and the previous year considered in the analysis t.

$$R_{t+1} = \left(f_{t+1}/f_t\right) * \left(G_{t+1}/G_t\right) * R_t$$

5

Translating the changes in environmental and social-economic indicators into SDGs progress. Firstly, the indicators selected for SDG in this study are from *the Global Indicator Framework for Sustainable Development Goals* developed by the United Nations' Inter-Agency and Expert Group on SDG Indicators [41], two reports titled "*Indicators and a Monitoring Framework for the Sustainable Development Goals*" and "*Sustainable Development Report 2020*" published by the United Nations' Sustainable Development Solutions Network [29,42], and a study entitled "*Assessing progress towards sustainable development over space and time*" published in Nature [43]. We choose SDG indicators (Table 1) based on the following three criteria: (1) the indicators are likely to be affected by electricity transition, (2) the indicators can be quantified across organizational levels and temporal scales, and (3) the data for quantifying the indicators are available from EXIOBASE[44] (see more detail about EXIOBASE in the next paragraph).

Table 1
Indicators selected for quantifying the impacts of power transition on SDGs

No.	SDG Indicators	SDG indicators illustration
1	SDG 6.4 Ensure sustainable withdrawals and supply of freshwater	6.4.1 Water-use efficiency: blue water consumption per GDP
		6.4.2 Level of water stress: blue water withdrawal as a proportion of available freshwater resources
2	SDG 7.2 increase substantially the share of renewable energy in the global energy mix	6.4 Renewable energy share in the power generation
2	SDG 8.4 Improve resource efficiency in consumption and production	8.4.1 (1) Domestic material use per capita: metal use per capita
		8.4.1 (2) Domestic material use per capita: non-metallic minerals use per capita
		8.4.1 (3) Domestic material use per capita: fossil fuels use per capita
		8.4.1 (4) Domestic material use per capita: biomass use per capita
		8.4.2 (1) Domestic material use per capita: metal use per GDP
		8.4.2 (2) Domestic material use per capita: non-metallic minerals use per GDP
		8.4.2 (3) Domestic material use per capita: fossil fuels use per GDP
		8.4.2 (4) Domestic material use per capita: biomass use per GDP
3	SDG 8.5 Achieve full and productive employment	8.5 Unemployment rate (% total labor force)
4	SDG 9.4 Promote clean and Sustainable industrialization	9.4 CO_2 emissions per unit of value added
5	SDG 11.6 Reduce the adverse per capita environmental impact of cities	11.6 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)
6	SDG 12.2 Achieve the sustainable management and efficient use of natural resources (same indicators in the official indicator book: 8.4.1/12.2.1, 8.4.2/12.2.2)	12.2.1 (1) Domestic material use per capita: metal use per capita
		12.2.1 (2) Domestic material use per capita: non-metallic minerals use per capita

No.	SDG Indicators	SDG indicators illustration
		12.2.1 (3) Domestic material use per capita: fossil fuels use per capita
		12.2.1 (4) Domestic material use per capita: biomass use per capita
		12.2.2 (1) Domestic material use per capita: metal use per GDP
		12.2.2 (2) Domestic material use per capita: non-metallic minerals use per GDP
		12.2.2 (3) Domestic material use per capita: fossil fuels use per GDP
		12.2.2 (4) Domestic material use per capita: biomass use per GDP
7	SDG 13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 CO_2 emissions intensity of forest areas
		13.2.2 CO_2 emissions intensity per capita
		13.2.3 CO_2 emissions intensity per GDP

Then, using 2015 as the baseline year, we calculate the score of selected SDG indicators for all 49 countries/regions in EXIOBASE 3. The procedure consists of following steps: To ensure data comparability across different SDG indicators, each indicator data is rescaled from 0 to 100, with 0 indicating worst performance and 100 denoting the optimum. Given rescaling is very sensitive to extreme (outliers) values on both tails of the data distribution, we follow the methods proposed by *Sustainable Development Report 2020* to determine the upper bound and low bound of each SDG indicator. We define the data at the bottom 2.5th percentile of all economies' SDG indicator performances for a given SDG indicator as the minimum value (0) and the data at the upper 2.5th percentile as the maximum value (100) for the normalization, for removing the effect of extreme values. In addition, we use net CO_2 emissions to set a 100% upper bound for SDG 9.4 and 13.2, as it must be achieved. After determining the upper and lower bounds, we rescale the selected SDG indicator values across economies to a scale of 0 to 100 with Eq. (6):

$$Z^{'} = \frac{Z - min(Z)}{max(Z) - \min(Z)}$$

6

where Z represents the raw data value for a given SDG indicator. Min and max is the bounds for the worse and best performance, respectively. $Z^{'}$ denote the normalized value for a given SDG indicator.

Declarations

Declaration of Interests

The authors declare that they have no competing interests.

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Figures

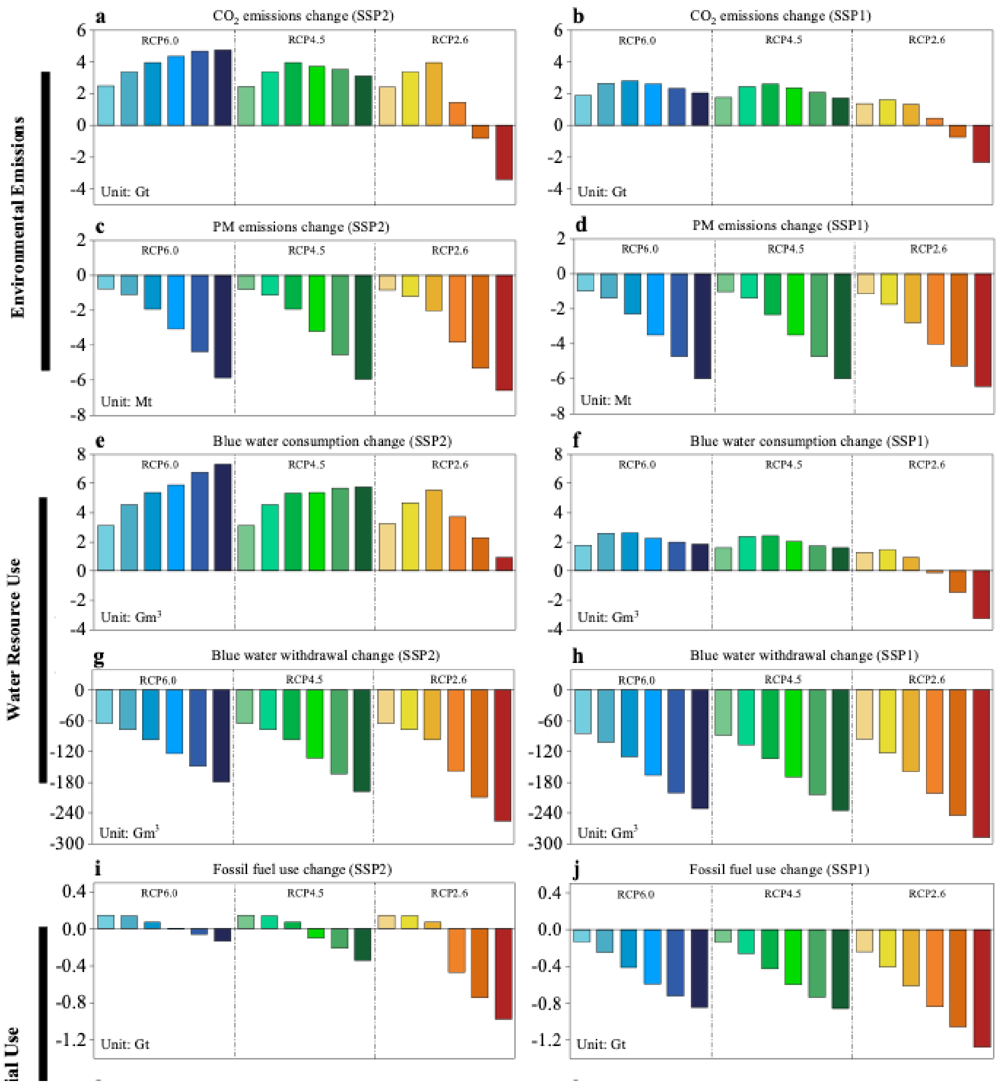

Figure 1

The net changes in environmental and socio-economic impacts of global power sector in 2025-2050 under six different scenarios to that in 2015. (**a-d**) environmental emissions, (**e-h**) water resources use, (**i-l**) material use, and (**m-n**) socio-economic impacts. Other material including biomass, metal, and non-metal minerals. The six different scenarios are SSP2+RCP6.0, SSP2+RCP4.5, SSP2+RCP2.6, SSP1+RCP6.0, SSP1+RCP4.5 and SSP1+RCP2.6.

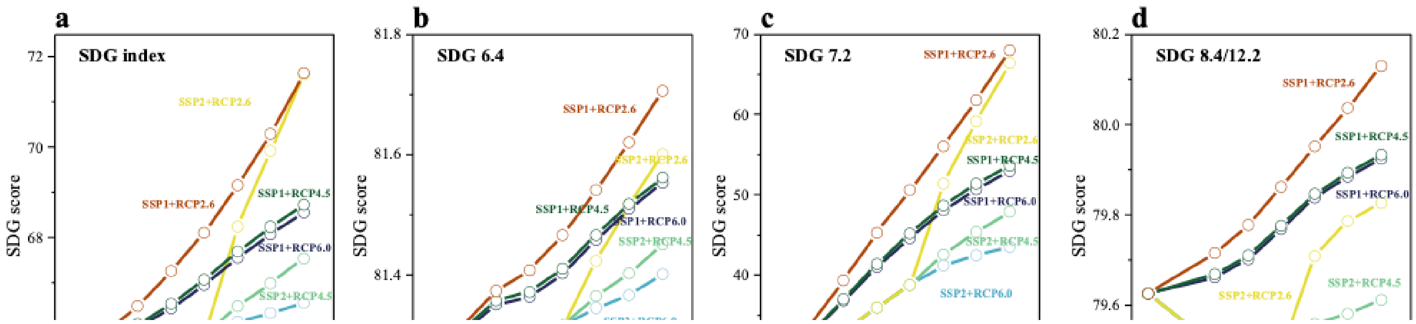

Figure 2

Global SDG index score and individual SDG score under six different climate scenarios. (a) global SDG index score and (**b-h**) scores of SDG 6.4 (Ensure sustainable withdrawals and supply of freshwater), SDG7.2 (increase substantially the share of renewable energy in the global energy mix), SDG 8.4 (Improve resource efficiency in consumption and production), SDG 8.5 (Achieve full and productive employment), SDG 9.4 (Promote clean and Sustainable industrialization), SDG 11.6 (Reduce the adverse per capita environmental impact of cities), SDG 12.2 (Achieve the sustainable management and efficient use of natural resources) and SDG 13.2 (Integrate climate change measures into national policies, strategies and planning). **Note**: To ensure comparability across different SDGs and different country/region, the SDG scores are normalized to a standard scale ranging from 0 (worst-performing in achieving SDGs) to 100 (best-performing in achieving SDGs).

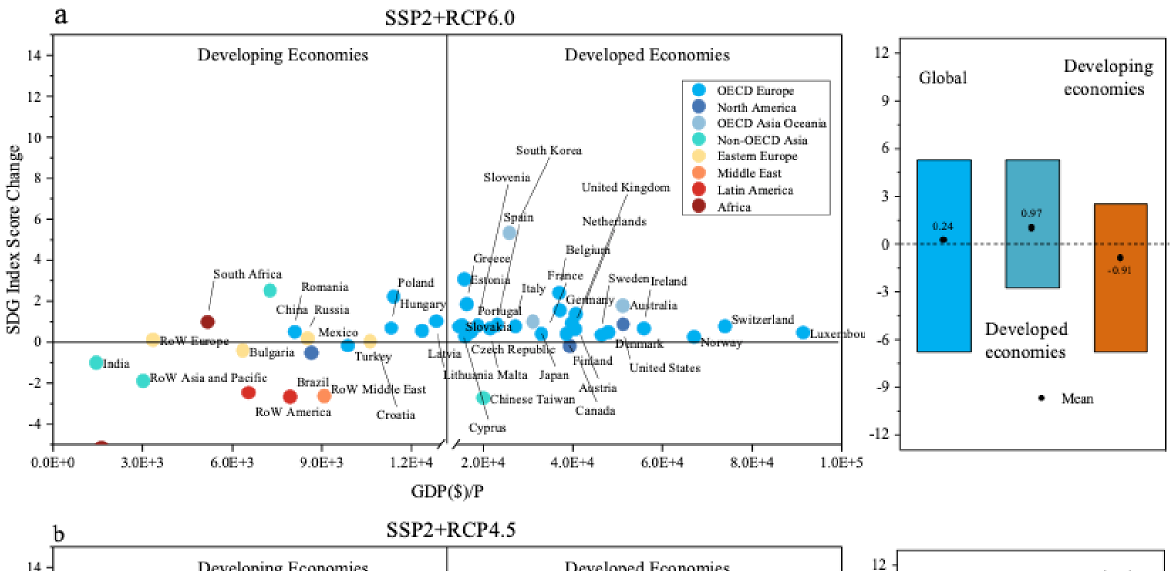

Figure 3

Changes of regional SDG index score (except SDG7.2) between 2015 and 2050 under SSP2+RCP6.0, SSP2+RCP4.5 and SSP2+RCP2.6 scenarios. (**a**) changes under SSP2+RCP6.0, (**b**) changes under SSP2+RCP4.5, (**c**) SSP+RCP2.6 scenarios and (**d**) score ranges and mean score.

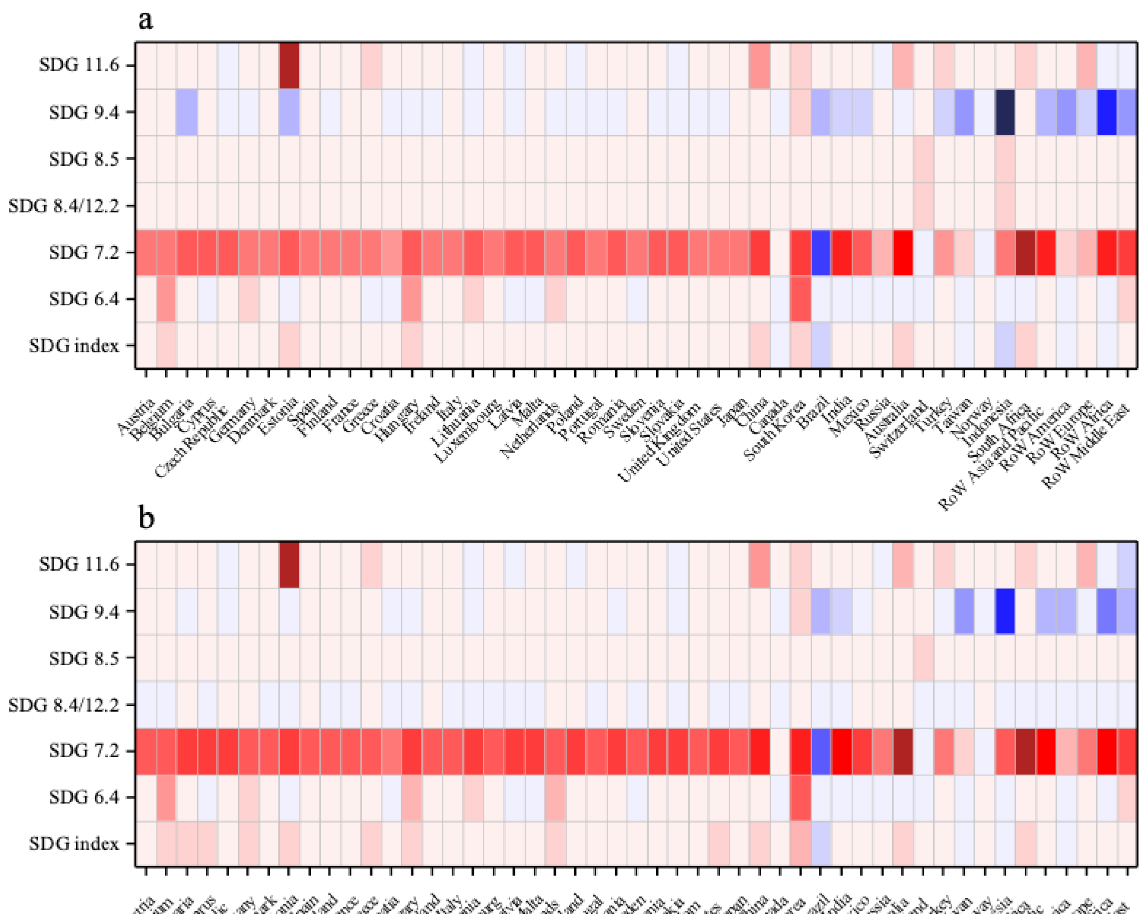

Figure 4

Changes of regional SDG index and individual SDG score between 2015 and 2050 under SSP2+RCP6.0, SSP2+RCP4.5 and SSP2+RCP2.6 scenarios. (**a**) SSP2+RCP6.0, (**b**) SSP2+RCP4.5, and (**c**) SSP2+RCP2.6.

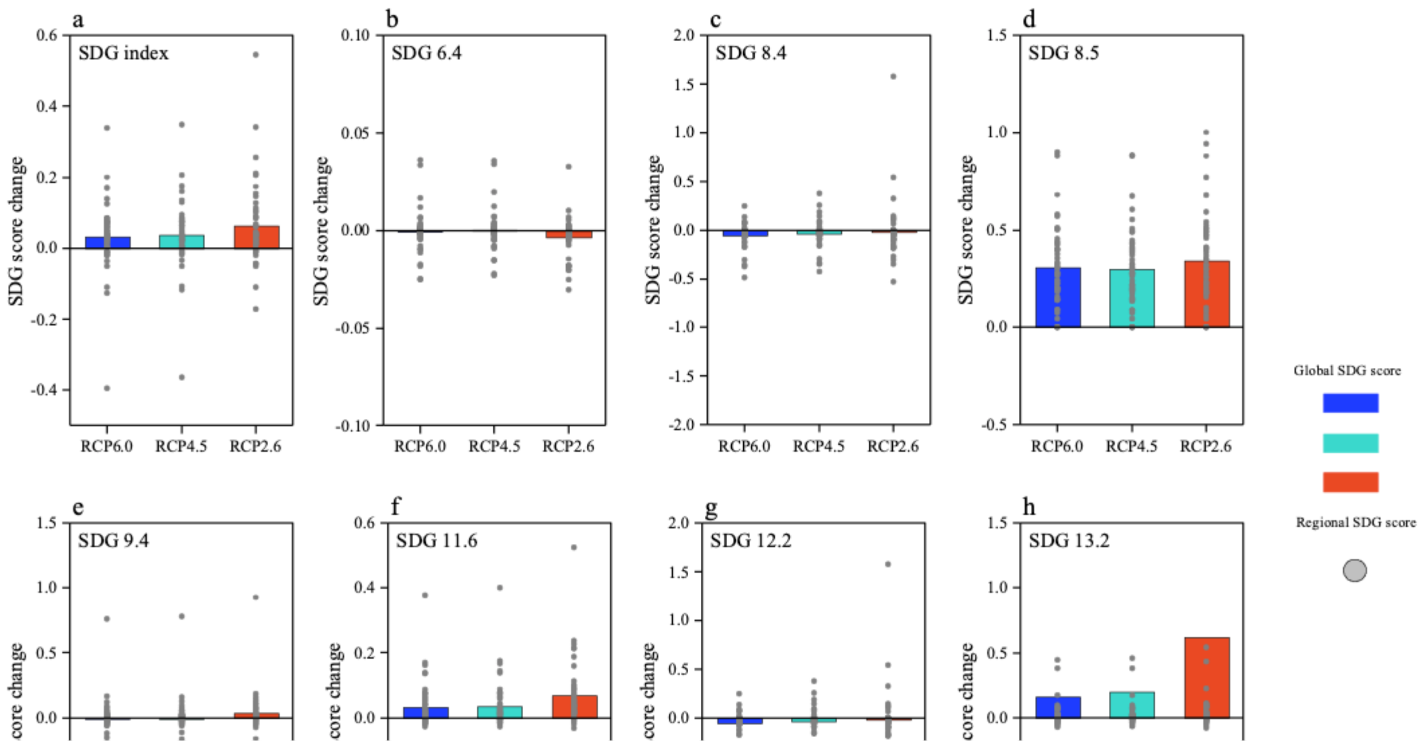

Figure 5

The impacts of power transition related international trade on global and regional SDG performance between 2015 and 2050 under SSP2+RCP6.0, SSP2+RCP4.5 and SSP2+RCP2.6 scenarios.

Supplementary Files

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