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Low carbon transition of global power sector enhances sustainable development goals

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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 assessed the potential impacts of power transition on 49 regional multiple SDGs progress under three different climate scenarios. We found that power transition could increase global SDG index score from 72.36 in 2015 to 74.38 in 2040 under the 1.5°C scenario, compared with 70.55 and 71.44 under ‘Coal-dependent’ and ‘Middle of the road’ scenario, respectively. The power transition related global SDG progress would mainly come from switching to renewables in developing economies. Power transition also improves the overall SDG in most developed economies under all scenarios, while undermining their employment-related SDG progress. The global SDG progress would be jeopardized by power transition related international trade changes under ‘Coal-dependent’ and ‘Middle of the road’ scenario, while improved under the 1.5℃ scenario.

Keywords: low-carbon transition; Global power sector; SDGs; Climate scenarios

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 [5].

However, power sector transition's impact is far beyond climate. It brings far-reaching effects on achieving Sustainable Development Goals (SDGs) [6], in terms of resources use[7,8], environmental emissions [3], employment [9], and many more[10,11]. What's more, power transition may reduce one problem while exacerbate others at times. For instance, the closure of coal-fired power plants will reduce cooling water withdrawal (advancing SDG 6: Clean Water and Sanitation) [12,13], 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) [14,15]. 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) [16], while increases demand for critical materials (hindering SDG 12: Responsible Consumption and Production) [17,18].

Previous studies have primarily demonstrated the impacts of specific national or regional power sector transition on a single aspect of sustainable development, such as regional employment [19], economic growth [20], natural resources use [21,22], greenhouse gas and pollutant emissions [23]. 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 [24]. 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, employment and value-added embodied in products and services from global supply chains, thus potentially influencing other regions' SDGs [25]. 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) [26]. Thus, we further highlight the role of international trade in regional SDG progress for preventing the power transition at the expense of SDG in other regions.

By applying Environmentally Extended Multiregional Input-Output Analysis (MRIO) and SDG assessment approach, here, we examine the direct and supply-chain effects of power transitions throughout the world on regional and global SDGs, including the net environmental, social, and economic changes under three climate mitigation scenarios (‘Coal-dependent’, ‘Middle of the road’ and 1.5℃ scenario) (**see detailed explanations in Methods**). Our findings demonstrate that low carbon transition of global power sector could enhance the overall SDG performance, but there are huge differences across individual SDGs in different economies.

Results

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

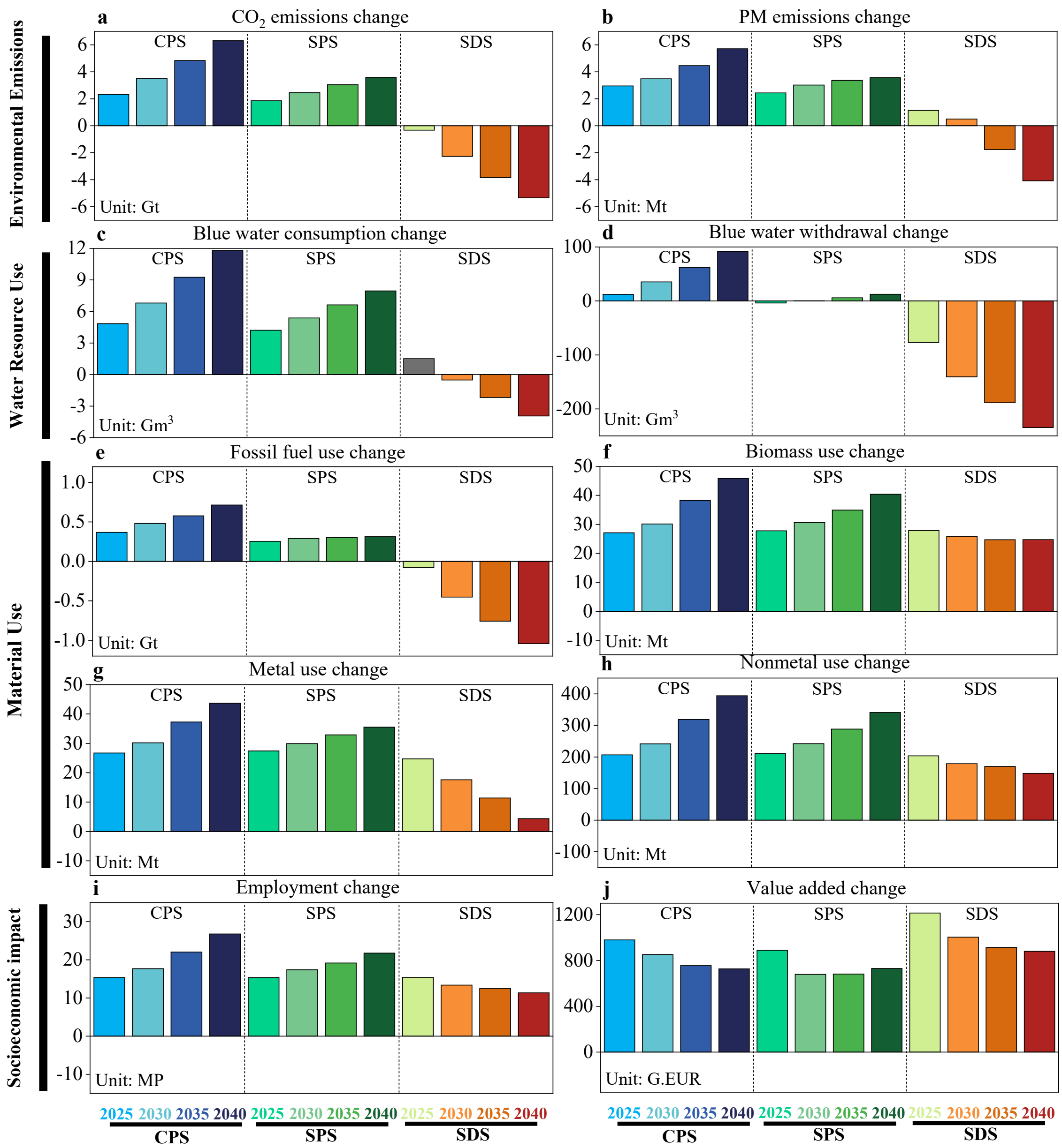


Figure 1. Comparison of the net changes in environmental and socio-economic impacts of global power sector in 2025-2040 under three different climate scenarios to that in 2015. (**a-b**) environmental emissions, (**c-d**) water resources use, (**e-h**) material use, and (**i-j**) socio-economic impacts. The three transition scenarios are Current Policies Scenario (CPS), Stated Policies Scenario

(SPS), and Sustainable Development Scenario (SDS), namely 'high coal' scenario, 'medium-sized coal' scenario, and 1.5℃ scenario, respectively.

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 three different climate scenarios-Current Policies Scenario (CPS), Stated Policies Scenario (SPS), and Sustainable Development Scenario (SDS), namely 'Coal-dependent', 'Middle of the road' and 1.5°C scenario, respectively.

From the figure we can see that global CO_2 emissions (**Figure 1a**) will increase by 10% and 18% under CPS and SPS scenarios between 2015 and 2040, but decrease by 15% under the SDS scenario. PM emissions (**Figure 1b**) show a similar trend with relatively small absolute changes. The discrepancy of emissions under different scenarios mainly results from the difference in energy mix of electricity production (**Table S1-S3**).

For water use, scenario results showed a similar trend as the changes in environmental emissions. Only SDS scenario results showed a significant annual decrease of 3.93 Gm^3 (-0.33%) blue water consumption and 234.61 Gm^3 (-17.2%) blue water withdrawal associated with power transition by 2040, compared with the increase of water use under the CPS and SPS scenarios (**Figure 1c and 1d**).

Given the higher demand for electricity in the future, all scenarios results showed an increasing use of materials, such as metal, non-metal minerals and biomass for power transition, except a decrease of fossil fuels under the SDS scenario (**Figure 1e-h**). However, compared with the CPS and SPS scenarios results, power sector would consume much less materials under the SDS scenario.

In terms of socio-economic impacts of the power production and transition, we can see a significant increase in both employment (**Figure 1i**) and value added (**Figure 1g**) under all scenarios, due to the high future demand of electricity. As coal power per unit of installed capacity can generate more jobs than that of renewables, but drive less economic output, our results showed that power generation and transition under the SDS scenario (the most ambitious scenario with renewables generation) may bring less job opportunities but create higher value added, compared with the results under CPS and SPS.

Power transition's impacts on global SDGs

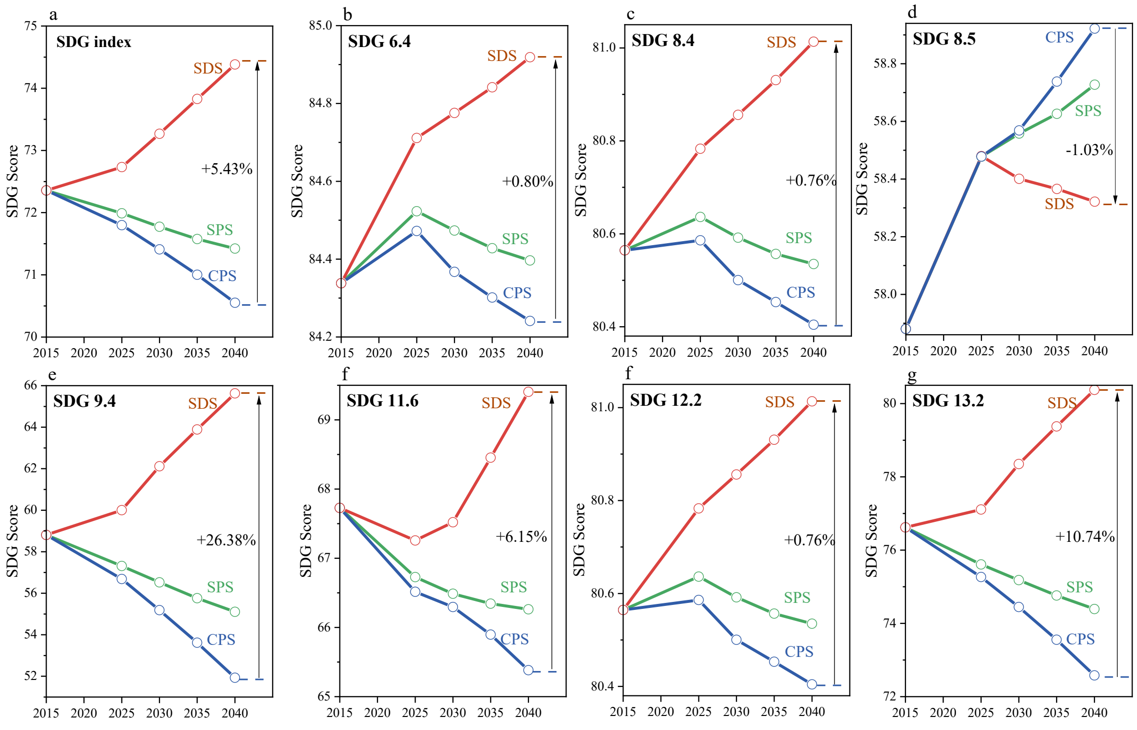


Figure 2. Global SDG index score and individual SDG score under three different climate scenarios. (a) global SDG index score and (**b-h**) scores of SDG 6.4 (Ensure sustainable withdrawals and supply of freshwater), SDG 8.4 (Improve resource efficiency in consumption and production), SDG 8.5 (Achieve 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).

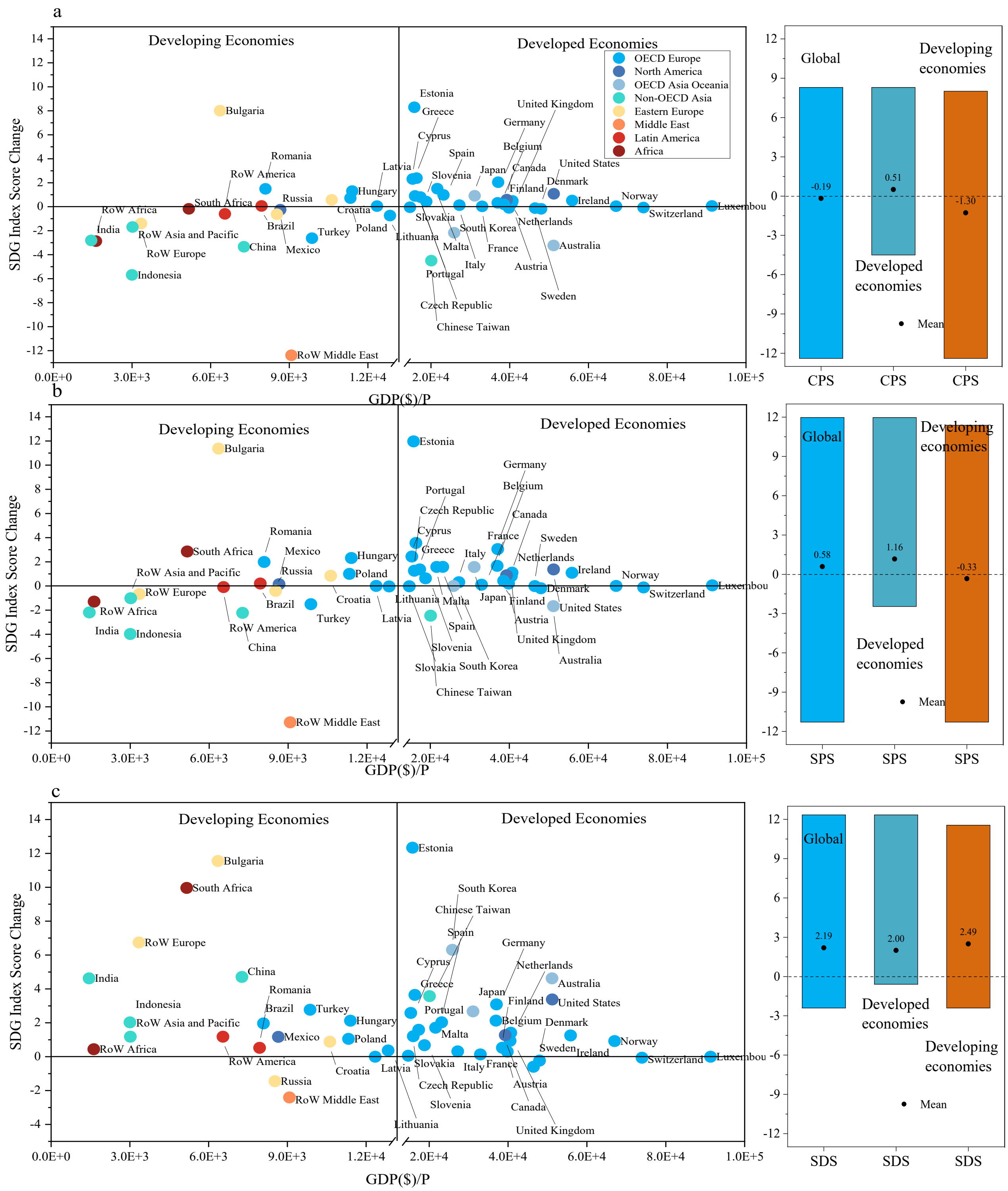
Here, we translated the changes in environmental and social-economic indicators into global SDGs progress using the United Nations SDG assessment approach (see method section). Our results showed that the global SDG index score, defined as the overall performance in achieving all individual SDG evaluated, will increase from 72.36 in 2015 to 74.38 in 2040 under SDS, while decrease to 70.55 and 71.44 in 2040, under CPS and SPS, respectively (**Figure 2a**). The fossil fuel for electricity generation plays a decisive role in global SDG performance of the power sector. As described in our three scenarios, global SDG index score only rises when fossil power generation drops (SDS), even though low-carbon power share will increase under each scenario.

Different power sector transition paths would undermine (**green and blue lines in Figure 2**) or underpin **(red lines in Figure 2)** individual SDG progress (**Figures 2b-**

2g). In 2040, SDG 6.4, SDG 8.4, SDG 9.4, SDG 11.6, SDG 12.2 and SDG 13.2 present higher scores under SDS scenario than the other two scenarios. The environmental and socio-economic benefits from the low carbon transition (SDS scenario) are intrinsically related to the reduction in blue water use, fossil fuels use, CO_2 and PM from the shutdown of a large number of thermal power plants (see **Table S1-S4**). However, CPS and SPS presents higher scores in SDG 8.5 (Achieve full and productive employment) (**Figure 2d**). For example, in 2040, SDG 8.5 score under SDS (57.88) is less than 1.03% of that under CPS (58.92). This is main because the shutdown of coal power under SDS would lead to a large number of unemployment in both coal power generation and upstream supply chains (e.g. coal mining sector).

The impacts of power transition on regional SDGs

SDG index score changes vary significantly across economies (**Figure. 3**). In general, the higher the GDP per capita is, the more inclined an economy is to improve the SDG index score and vice versa (**Table S4**). During the period of 2015-2040, the average SDG index scores of developed economies will increase by 2 percentage points and almost every developed economy improves their SDG scores to some extent under the SDS scenario. However, close to 30% of the developed economies may face a decline in their SDG scores under the CPS scenario. In contrast, more than half of the developing economies, mainly from Asia and Africa, will have a decline in their SDG scores under the CPS scenario, while this number decreased to about 20% under the SDS scenario.



(**a**) changes under CPS, (**b**) changes under SPS, (**c**) changes under SDS and (**d**) score ranges and mean score.

Estonia, one of the countries that most dependent on fossil power, is top economy in SDG index score increase by 2040 under all scenarios, with a range of 8.29 to 11.33, as it expects to significantly replace coal power through the development of renewable energy such as wind power and biomass affected by European Climate Law. This verifies that strict climate legislation can effectively improve the sustainable development level of regions highly dependent on fossil power. In contrast, Middle East is the economy with the biggest drops in SDG index score from 2.40 to 12.39, because it will still develop gas power substantially.

SDS shows that regional power transition can also lead to synergies and trade-offs between different individual SDGs (**Figure 4c**). As for synergies, more than 80%, 60%, 60%, 85%, 60%, and 80% of countries or regions will have an increase in SDG 6.4 scores, SDG 8.4/12.2 scores, SDG 8.5 scores, SDG 9.4 scores, SDG 11.6 scores, SDG 13.2 scores. However, there is a trade-off between SDG 8.5 and SDG index. For example, under SDS, Bulgaria's SDG index score will increase by 11.55 in 2040, but due to the loss of employment during the transition, its SDG 8.5 score fall by 0.05. In addition, the power transition of some will increase all individual SDGs score, such as United State, India, South Africa.

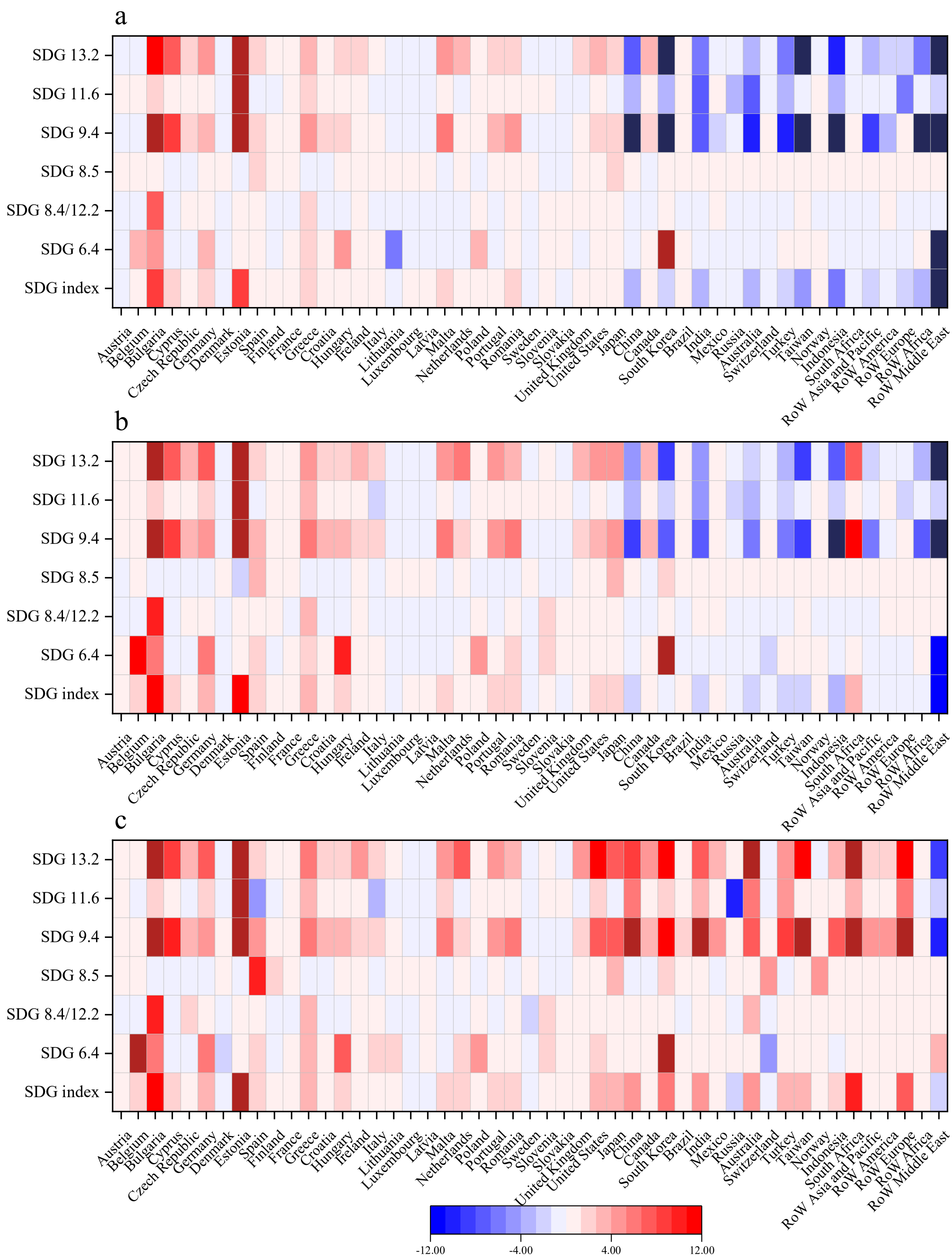


Figure 4. Changes of regional SDG index and individual SDG score between 2015 and 2040 under three scenarios. (**a**) CPS, (**b**) SPS, and (**c**) SDS.

The effects of power transition related international trade changes on SDGs

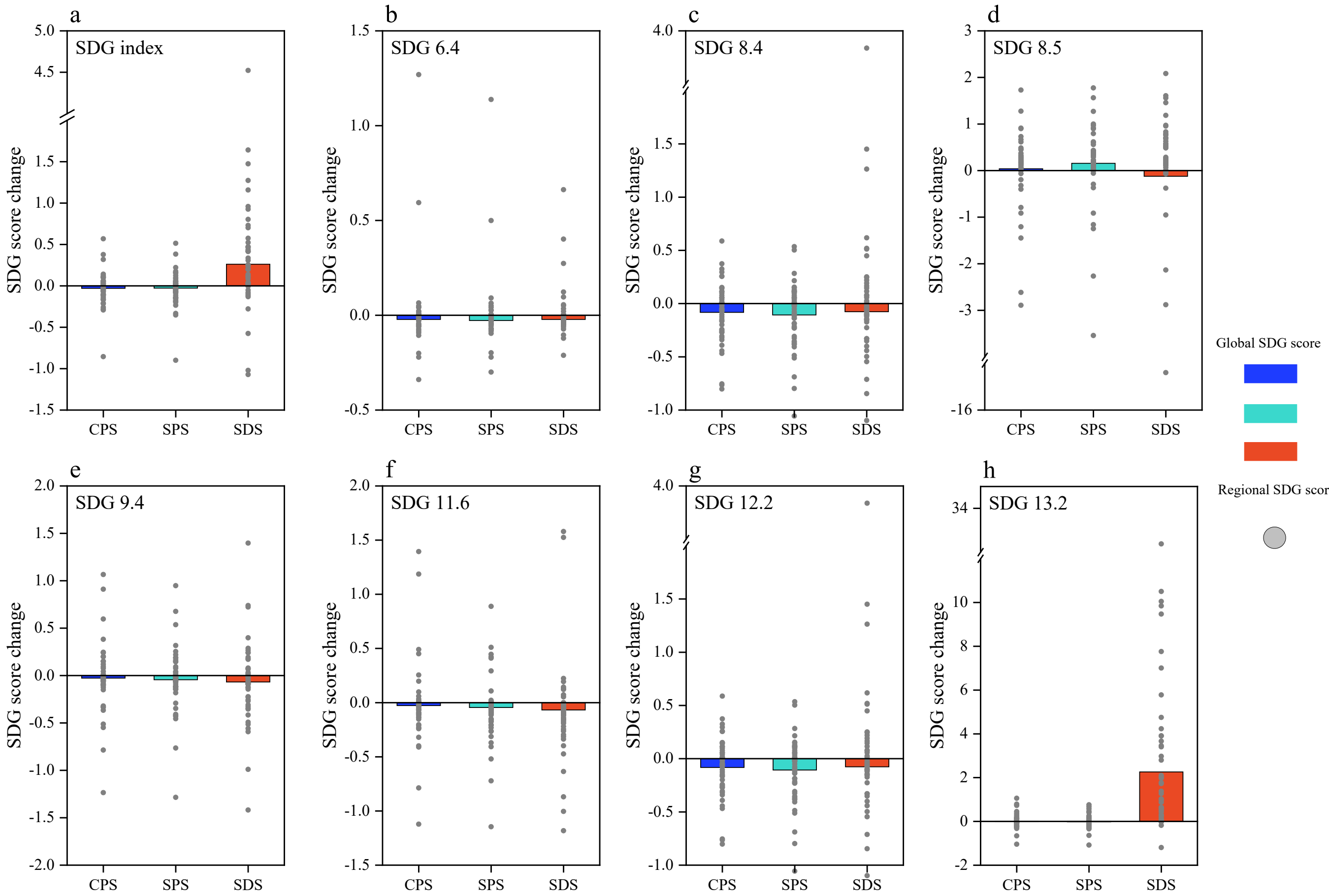


Figure 5. The impacts of power transition related international trade on global and regional SDG performance between 2015 and 2040 under three different scenarios.

The power transition will change the scale and category of international trade for renewable equipment and traditional power fuels between different economies and lead to the changes in environmental emissions, resources consumption, employment and value-added embodied in exports and imports, thus influencing SDG performance in different regions. Under SDS scenario, the international trade will improve the overall SDG performance (0.37%) globally between 2015 and 2040, while the results are opposite (about -0.04%) under the CPS and SPS scenarios (**Figure 5a**). However, the overall impacts of changes in international trade on the global SDG performance are quite limited, as the traded commodities and services related to power sector only account for less than 2% of the international trade, in terms of economic value. Climate-related SDG (SDG 13.2) performance will have highest degree of improvement (2.95%), mainly due to the reduction of CO_2 emissions embodied in thermal power-related trade, under SDS (**Figure 5h**). Under CPS and SPS, the employment-related SDG (SDG 8.5) performance will be improved (0.07-0.28%), mainly because of the expansion of labor intensive renewable power sectors (**Figure 5d**). However, all scenarios showed a decline (0.03-0.13%) in the average scores of resource-related SDGs (SDGs 6.4, 8.4 and 12.2), due to the increase in power production related resource use met by international trade (**Figure 5b, c and g**). The increasing resource use for power transition may also lead to a decrease in the average scores of SDG 11.6 (Reduce the adverse per capita environmental impact of cities) by 0.04-0.1% under all scenarios (**Figure 5f)**.

From a regional perspective, more than 80% of economies would improve their SDG performance under SDS (**Figure 5**). The countries/regions with rich fossil energy resources, such as the Middle East, Czech Republic, Slovakia, ranked at the top in term of SDG index score increase. This is mainly because other economies' low-carbon power transition inevitably leads to the decrease of fossil fuel imported from these regions, potentially reducing their resource extraction and related environmental impacts. For example, under the SDS scenario, oil exports from the Middle East for other economies' power production would be reduced by 65%, which result in a 0.28% increase in its SDGs 8.4 (Improve resource efficiency in consumption and production) score. In contrast, jobs will be wiped out in these fossil fuel export-dependent regions such as Australia, as a result of the coal export deceases, therefore, leading to a 0.07% of decrease in its employment-related SDG score (SDG 8.5). However, under CPS and SPS, most of the individual economy's SDG progress (about 60%) would be impeded by international trade, as the expansion of fossil fuel based power production leads to the increase of power sector related resource consumption and environmental emissions embodied in international trade. For instance, Russia, as a resource-rich economy, will export more fossil resources to support power expansion of other economies, resulting in an increase (about 7%) of carbon emissions embodied in its exports, and a decrease (about 3%) of its climate-related SDG performance (**Table S5 and S6**).

Discussion

For the first time, we performed a quantitative analysis of power sector transition's impacts on global and regional multiple SDGs performances. We found the evolution of global SDG index score (the average score of seven selected SDGs) during 2015-2040, is opposite under different climate scenarios. Power transition brings an increase of 2.8% (72.36 in 2015 to 74.38 in 2040) in global SDG index score under the 1.5℃ scenario (i.e. SDS), while leads to a reduction of 1.3-1.5% (72.36 in 2015 to 70.55-

71.44 in 2040) under the ‘high coal’ and ‘medium-sized coal’ scenario (i.e. CPS and SPS).

We also found that there are significant differences across regional SDG index score changes. From 2015 to 2040, the regional SDG index score change is estimated to be in the range of -12.39 (Row Middle East) to 8.29 (Estonia), -11.28 (Row Middle East) to 11.97 (Estonia) and -2.4 (Row Middle East) to 12.33 (Estonia), under CPS, SPS and SDS, namely ‘Coal-dependent’, ‘Middle of the road’ and 1.5°C scenario respectively. In addition, the change of regional individual SDG score isn’t always consistent with that of SDG index score. For instance, resource-related SDGs (SDGs 8.4 and 12.2) on 17 of the 49 economies, on the contrary, will become worse if the currently fossil-dominated power structure transited to a renewable-dominated one (1.5℃ scenario).

According to Sustainable Development Report 2020, the progress of achieving the SDGs by 2030 lags far behind the schedule predesigned by the UN [27]. One of the main reasons is that there is a lack of understanding of the interactions between SDGs [28], which is essential to trade-offs between SDGs and advance the overall SDGs with minimal efforts[11]. 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”.

Developing economies’ lower 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 2040, which is much higher than that of the developed economies (23.2-28.4%) [5]. 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 [29]. 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 [5]. 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 [30]. 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 1.5°C pathway (or rapid low-carbon power transition) was verified that it can bring co-benefits to global SDGs performance on the whole. However, the situation in each region differs from one another. All individual SDGs in these nine economies, Australia, Ireland, United States, Chinese Taiwan, RoW America, South Africa, RoW Europe, RoW Asia and Pacific, India, 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) [31]. 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 will cause conflicts between individual SDGs progress (where progress in one goal hinders progress in another), so thus hinder SDGs progress. For example, the expansions of wind power in Germany 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, it is critical to increasing secondary supply of materials (recycle) other than exploiting mines. Given the low rate of recycling of materials and high recycling costs in power sector, more efforts need to be exerted into the centralized recovery of retired electrical equipment and the development of technologies that have lower costs and higher recovery rates. The social justice issues come from laid-off workers caused by the decommissioning of coal power plants. For example, 4.9 million coal power-related workers will be unemployed in China in 2040 under SDS. Coal electricians and upstream coal miners are difficult to get reemployed due to their limited skills. Coal-transition support is, therefore, a necessary measure for coal workers and should be considered by policymakers in coal-dependent countries.

Our results also indicate that international trade associated with the power sector has a limited effect on the global overall SDG performance, but it will profoundly affect the SDG process of individual countries. This means cross-national inequities in achieving SDGs progress may be exacerbated as the expansion of renewable power or the reduction of fossil fuels in the electricity mix. For example, under SDS, in 2040, 55.9% of metal use increases (hindering SDG 8.4 and 12.2) in the Row Europe are caused by power transition in the country itself, and the remaining 44.1% are driven by the other countries (advancing SDG 9.4 and 13.2) low-carbon transition's ripple effects throughout global supply chains. This emphasizes power transition as a global systemic phenomenon, instead of looking at the area of power installation in isolation, which calls for taking consumption-based accounting principle into considering when formulating power transition strategies to facilitate best practice in minimizing impacts on SDG.

Limitations and future works

This study employed the labor data in EXIOBASE 3 to analyze the impact of power transition on regional employment. Although this data is more detailed on sector classification than other authority's data, such as International Labor Organization, it divides the broad renewable sector's employment into detailed industries (such as wind power, PV) according to their shares in total compensation of employees, and does not distinguish the employment coefficients difference between different renewable power sectors. This may leave uncertainty in our employment accounting in renewable sectors. In future research, more detailed employment survey data in renewable sectors is needed to reduce the uncertainty of analyzing power transitions' impact on employment. Moreover, the power transition is part of the energy transition, which also includes industry and residential sectors' transition etc. Combining with the foundation lied by this study, future studies can focus on much bigger picture, try to reveal the entire energy system transition's influence on SDGs performance.

Methods

Three climate scenarios

The three climate scenarios (Current Policies Scenario, Stated Policies Scenario, and Sustainable Development Scenario, namely 'Coal-dependent', 'Middle of the road' and 1.5°C scenario, respectively) were derived from the latest IEA's Word Energy Outlook report. Current Policies Scenario is the most fossil-dependent scenario, in which coal-fired electricity generation, with an amount of 12923 TWh, accounts for 30% of electricity supply and gas-fired generation for about 25% by 2040. Under Stated Policies Scenario, coal-fired electricity generation's share of overall generation will decline from 38% to 25% and the share of generation from renewables increases from 26% today to 44% in 2040, with solar PV and wind together rising from 7% to 24%. Sustainable Development Scenario has the most ambitious scenario with renewables generation to keep global temperature rise below 1.5°C above the pre-industrial level. The growth of renewables generation raising their share of generation to two-thirds by 2040. Wind and solar PV together provide 40% of generation in 2040. More details about the three scenarios can be found in the IEA's Word Energy Outlook.

Indicator selection and data sources for SDG

The indicators selected for SDG in this study were from *the Global Indicator Framework for Sustainable Development Goals* developed by the United Nations' Inter-Agency and Expert Group on SDG Indicators [32], 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 [27,33], and a study entitled "*Assessing progress towards sustainable development over space and time*" published in Nature [34]. We chose SDG indicators 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[35] (see more detail about EXIOBASE in the next paragraph).

Calculating the scores of selected SDG indicators

Using 2015 as baseline year, we calculated the score of selected SDG indicators for all 49 countries/regions in EXIOBASE 3. The procedure comprised following steps: To ensure data comparability across different SDG indicators, each indicator data was 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 followed the methods proposed by *Sustainable Development Report 2020* to determine the upper bound and low bound of each SDG indicator. We defined 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 used 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 rescaled the selected SDG indicator values across economies to a scale of 0 to 100 with equation (1):

$$Z' = \frac{Z - min(Z)}{max(Z) - min(Z)} \times 100 \quad (1)$$

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.

MRIO analysis for estimating the impacts of electricity transition on SDG progress

First, we applied Input-Output analysis (IOA) to quantifying the environmental-social-economic impact of power sector in 2015. This model captured both direct and indirect effects of eleven electricity 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, tide, wave, ocean power, and geothermal power) on environmental emissions, water resources use, material use, employment and value-add. The basic framework of IOA is as follow:

$$X = (I - A)^{-1} Y \quad (2)$$

where $X = \left[X_i^r \right]_{n \times 1}$, X_i^r is the total output of *i*th sector in region *r*. *I* is the identity matrix. $A = \left[A_{ij}^{rs} \right]_{n \times n}$ 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* and X_j^s is the total output of *j*th sector in region *s*. $Y = \left[Y_i^{rs} \right]_{n \times m}$ is the final demand matrix, Y_i^{rs} represents the final demand of region *s* for the goods and services of *i*th sector from region *r*.

Total (including direct and indirect) environmental-social-economic impact of one of electricity production sub-sectors can be mathematically expressed as:

$$R = f\left(I - A\right)^{-1} X' \tag{3}$$

where f is a matrix of the environmental emissions, water resources use, material use, employment and value-add intensity (the direct environmental emissions, water resources use, material use, employment and value-add per unit total output from each sector) for all economic sectors in all regions. X' is the total output matrix with zeros for all sectors' total output other than the electricity production sub-sectors.

In addition, we define the difference between the total impact and the direct impact (E, the direct environmental emissions, water resources use, material use, employment and value-add) as the impact of trade (T).

$$T = R - E \tag{4}$$

Declaration of Interests

The authors declare that they have no competing interests.

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

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 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
		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

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