



Carbon emission intensity of electricity generation in Belt and Road Initiative countries: a benchmarking analysis

Xingping Zhang^{1,2} · Haonan Zhang¹ · Changhong Zhao¹ · Jiahai Yuan^{1,2}

Received: 13 December 2018 / Accepted: 13 March 2019 / Published online: 27 March 2019
© Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract

The scope of this study is to analyze the carbon emissions intensity of electricity generation in “Belt and Road Initiative” (BRI) countries. The total CO₂ emissions from electricity generation in BRI nations increases from 4232.34 Mt in 2013 to 4402.38 Mt in 2015, accounting for 34.45% of global CO₂ emissions from electricity generation. Logarithmic mean Divisia index methodology is applied to analyze the drivers of carbon emissions intensity in BRI nations. The decomposition results revealed that the regional carbon emissions intensity in BRI nations increases during 2013–2015 and the power generation efficiency is the essential factor to improve carbon emissions performance in BRI developing countries. For BRI developing countries, promoting clean and efficient thermal power is a pragmatic priority for green power development.

Keywords The Belt and Road Initiative (BRI) · Carbon emission intensity · LMDI

Introduction

On 10 September 2013, Chinese President Xi Jinping successfully proposed the construction of two major initiatives during the visit to Central Asian and Southeast Asian nations: “Silk Road Economic Belt” and “21st Century Maritime Silk Road” which were collectively called the “Belt and Road Initiative” (BRI) (State Council 2015). The wisdom of jointly building through consultation to meet the interests of all nations has attracted close attention from all over the world. The energy cooperation has been a priority and significant pillar of economic and social activities and cores of regional development. The effects of trade integration and regional cooperation on energy efficiency convergence are positive across regional cooperation organizations and the world, with a much stronger influence among middle- and low-income BRI nations (Han et al. 2018). Li et al. (2018a, b) insisted that the BRI can

promote the global carbon emissions reduction and the positive impacts on carbon intensity depends on the surrounding areas, indicating that the low-carbon development is a global governance issue. The carbon emissions from electricity production in BRI nations (excepting China) accounts for 34.4% of that of the world in 2015. However, the carbon emissions reduction issues are given scant attention in BRI nations, most of which have submitted explicit targets for Intended Nationally Determined Contributions (INDC). In the global trend of efficient, clean, and low-carbon energy transition and environmental governance, the BRI energy cooperation could potentially drive the performance of carbon emissions reduction by promoting the power generation technology and renewable energy utilization, etc.

In 2016, there are about 370 million of the population without access to electricity service, mainly distributed in Southeast Asia, South Asia, and Africa (WDI 2018). Ensuring access to affordable, reliable, sustainable, and modern energy is the essential target of Sustainable Development Goals (SDGs) proposed by United Nations in 2015. Electricity has been recognized as safe, extensive, convenient, and efficient energy source for social and economic development. Yuan et al. (2018) estimated the increments of thermal power and renewable energy installations would be 1464 GW and 1960 GW, respectively, in BRI nations in 2030. In short, if appropriate measures are taken to reduce the carbon emissions intensity, we could restrain the

Responsible editor: Philippe Garrigues

✉ Jiahai Yuan
yuanjh126@126.com

¹ School of Economics and Management, North China Electric Power University, No 2, Beinong Road, Beijing 102206, China

² Beijing Key Laboratory of New Energy and Low-Carbon Development (North China Electric Power University), Changping, Beijing 102206, China

related emissions increasing caused by power demand growth. Therefore, understanding the drivers of CO₂ emissions is significant for energy policy, INDC targets, and sustainable development in BRI nations.

With the increasing reliance on electricity due to people's desire for comfortable life, the power industry will become the pillar of the cross-network of economy growth, energy supply, and environment protection, to some extent. Global electricity consumption has increased tremendously, from 14,193.48 TWh in 2000 to 22,385.81 TWh in 2015, and the CO₂ emissions of electricity and heat production has increased from 9.45 billion tons to 13.54 billion tons (IEA 2018). Despite the extensive development of renewable energy significantly mitigating the global carbon emissions level, the traditional fossil power has been thriving on the competitive cost, especially in the BRI developing countries. In the short terms, fossil energy will remain top priority for low-income countries. Therefore, improving the thermal generating efficiency is an important avenue to reduce emissions.

Researches on carbon emissions are massive and comprehensive. The carbon emissions are closely associated with human activity. Generally, there is a significant cointegrated relationship between real GDP, energy consumption, and carbon emissions (Fei et al. 2011; Hamit-Haggag 2012; Kais and Sami 2016; Niu et al. 2011; Ozcan 2013; Yuan et al. 2014a). Liu and Hao (2018) confirmed strong nexuses among carbon emissions, energy use, industry value added, and GDP per capita in the BRI nations. Li et al. (2018a) concluded the BRI could promote to mitigate the global carbon emissions due to the investment rate and openness driving the decrease of carbon intensity growth rate. Dai et al. (2016) used the LMDI theory to discuss the decoupling between GDP and energy-related CO₂ emissions in BRICS countries from 1995 to 2014. Li et al. (2018b) analyzed the driving factors for carbon emissions from the power sector in 11 countries accounting for 67% of the global emissions between 1990 and 2013. Madaleno and Moutinho (2017) applied the LMDI method to decompose carbon emissions into six effects: carbon intensity, fossil fuel consumption, energy intensity, oil imports intensity, oil dependence, and population effect. Yan et al. (2016) employed LMDI methodology to analyze the CO₂ emissions from thermal power generation at the regional grid level in China during 2000–2012. Yu et al. (2018) analyzed the carbon emissions intensity convergence of 24 industrial sectors in China between 1995 and 2015 by applying environmental performance index method and the convergence model. Malla (2009) examined the impact of three factors (power production, power generation structure, and energy intensity of power generation) to carbon emissions from electricity generation sector in seven Asia-Pacific and North American countries during 1990–2005. Wang et al. (2017) applied multi-region structural decomposition analysis (SDA)

technique to identify the changes of carbon emissions intensity in global and nations from 2000 to 2009. Sun et al. (2017) indicated that the sectors of electricity, gas, and water supply accounted for 60% of the CO₂ emissions of secondary industry from the production perspective in India during 1995–2009 by applying the SRIO model. Tang et al. (2017) revealed the high trade-off cost for China to reduce embodied emissions exports by using a trade restructuring optimization model combined with input–output analysis and multi-objective programming. Ji et al. (2019) investigated the information spillover between carbon price returns and stock returns of 18 top European electricity companies. Peng et al. (2018) employed the global multi-regional input–output table to analyze the critical supply chain paths for the carbon emissions from China's iron and steel industry. These studies provide detailed discussions on carbon emissions issues by employing various methods, which has critical impact on low carbon policy making and action guidance.

To gain an accurate estimating of CO₂ emissions performance in the power sector, it would be sensible to eliminate the impact of potential growth in electricity demand first. This can be addressed through normalizing the related CO₂ emissions. An appropriate indicator “aggregate carbon intensity” (ACI) was presented by Ang et al. (2011) to investigate the global potential for reducing CO₂ emissions by using 2005 data of world countries. He considered four impacting factors from the perspective of system analysis: (1) the proportion of power generated from fossil fuels, (2) the fossil fuel mix in power generation sector, (3) the thermal generation efficiency of fossil fuels, and (4) the carbon emission factors for fossil fuels. Ang and Su (2016) extended this earlier study to a temporal one by using the data of 124 countries together accounting for 97% of 2013 world electricity production. ACI is an indicator for the ratio of total CO₂ emissions from electricity generation to the total electricity generated in the country (expressed in kg CO₂/kWh). As an aggregate indicator, it may be estimated at the country, regional, and global level. The decreasing ACI value indicates a lower level of CO₂ emissions intensity than otherwise, which is regarded as positive performance from the energy conservation and climate change viewpoint. ACI is easily computed and compared across the countries (regions) and over time.

This study focuses on the potential for reducing carbon emissions from electricity generation in BRI nations, as well as in China, America, European Union, and global aggregate for comparison. As aforementioned comparison across the countries and over time, we analyze the ACI performance using the 2013 and 2015 data in as many countries as data permit. And compared with the results of Ang and Su (2016), the distinct changes in various counties are highlighted between 2013 and 2015 and 1990–2013. The contribution of this study is to explore the essential impacting function on carbon emissions from electricity generation in BRI nations

to advise on future energy cooperation. It should be emphasized that the data and results in this study provide the benchmarking analysis of reducing carbon emissions performance in power sector, without considering the fundamental factors impacting the electricity generation, such as energy resource endowment, power supply costs, electricity market, national policies, and other geographical factors.

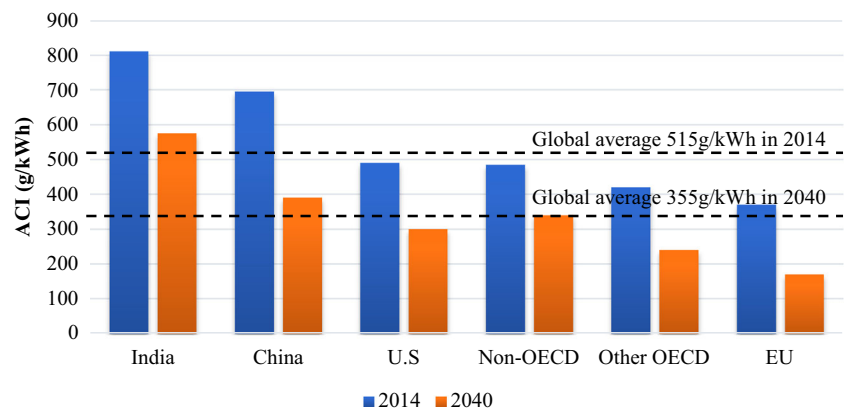
The remainder of this study is organized as follows. Section 2 presents the brief overview on carbon emissions intensity from power sector in the world and BRI nations. Section 3 introduces the data and LMDI technique. Then, the empirical results and discussion on regional and national ACI are presented in Section 4. Finally, Section 5 concludes the paper with policy implications.

Global and BRI nations aggregate carbon intensity

Main factors at the global level

The proportion of CO₂ emissions from electricity and heat generation reached 41.9% of the global fuel combustion. From 2000 to 2015, global CO₂ emissions from electricity production increased from 6282 to 11,749 Mt CO₂ and electricity generation increased from 11,627 to 22,592 TWh. The average ACI of electricity generation in 2000 and 2015 were 533 g/kWh and 506 g/kWh, respectively. A decrease of 27 g/kWh or 5% of the 2000 level over the period was observed, which benefited from the breakthrough of fossil energy generation efficiency and renewable energy development. The margin of improvement remains technically great because the ACI in China and India as the two countries with the most prominent carbon emissions was 695 g/kWh and 810 g/kWh, respectively, in 2014 (shown in Fig. 1). In the IEA new policies scenarios, the carbon intensity of coal and natural gas generation is expected to decrease to 855 g/kWh and 385 g/kWh, respectively, contributing to the global ACI decreasing from 515 g/kWh in 2014 to 335 g/kWh in 2040 (IEA 2016a).

Fig. 1 ACI of power sector in major electricity producers in 2014 and 2040



The proportion of coal power was at the peak in the global power generation in 2015, accounting for 39% (shown in Fig. 2). Gas power and renewable energy matched in the generation, up to proportion of 23%. Influenced by resource endowment, power installation has obvious regional characteristics. It is observed that coal power is concentrated in East Asia, South Asia, and Southeast Asia, while gas and oil power are dominating in Middle East. As is well known, there is a tight causal relationship between carbon emission, electricity consumption, and economic growth. Ersin et al. (2016) investigated the relationship between electricity consumption and economic growth in 64 countries from 1971 to 2008 by using the concept of hierarchical structure methods and hierarchical tree. They found a strong relation between energy consumption and economic growth for all the income groups, which was in good agreement with the causal relationship between electricity consumption and economic growth. Understanding the drivers or determinants of carbon emission in electricity generation is essential for assessing the future emission trends and power development strategies.

A brief overview of BRI nations

According to incomplete statistics, the total power installed capacity in BRI nations is up to 1659 GW in 2016, among which coal power, oil and gas power, renewable energy, and nuclear account for 32.7%, 38.6%, 23.8%, and 4.9%, respectively (shown in Fig. 3). The coal power installed capacity in BRI nations accounts for 27.1% of global coal power installation, which would rise to 74% if China is included. Indeed, the coal power units permitted and under construction in BRI nations accumulatively reach 387.7 GW, accounting for 59% of global coal power planning. Similarly, if China is added, it will reach a terrifying 91%. Newly built coal power plants will inevitably lead to carbon emissions increasing, especially in developing countries with poor environmental standards. Other than reducing the fossil power planning, an appropriate approach to help reduce the growth of CO₂ emissions from

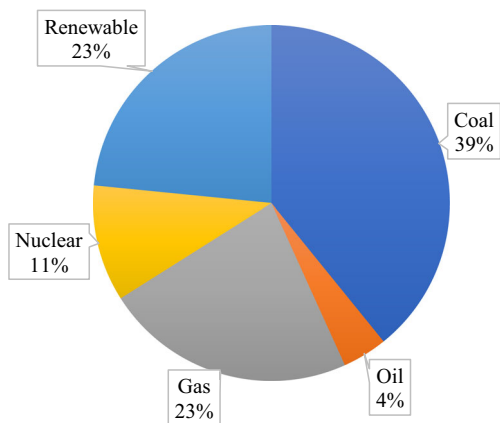


Fig. 2 Structure of global power generation in 2015. Data sources: IEA statistical database (<http://www.iea.org/classicstats/statisticssearch/>)

power generation is to focus on the power plant thermal efficiency and fossil fuel equality.

The three principal characters of current power industry in BRI nations are represented as (1) fossil power generation still occupying the dominate status now and the future; (2) renewable energy becoming the global investment hotspot, especially in Asian and African countries; and (3) disparate gap in national per capital power installation. Bahrain has the largest per capital installed capacity with 4.12 kW/per, while Afghanistan has the poorest with 0.015 kW/per. Considering the national diversity in economy, resource endowments, and environmental policies, power cooperation should adhere to the principle of adapting to local conditions for both thermal power and renewable energy. The priority of electricity industry development is to enhance energy efficiency in BRI nations. Then, clean and efficient coal power and affordable and available renewables are the pillar of low-carbon transition.

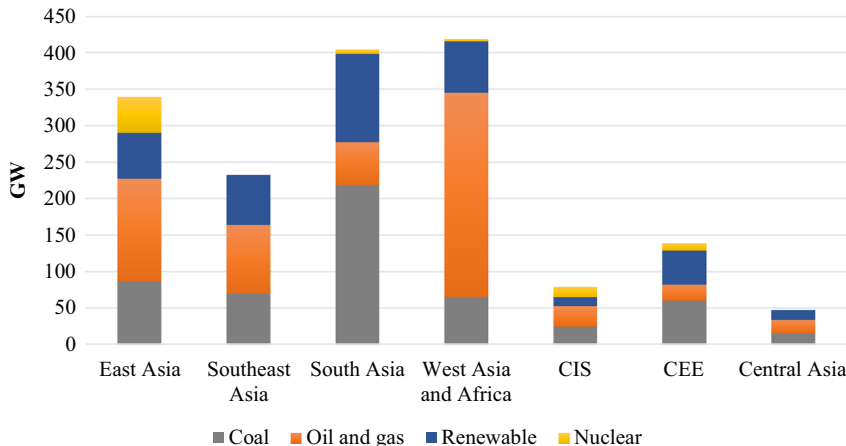
Out of the 76 BRI nations published on the official website, the annual generation of 62 countries with detailed data accounts for 28.6% of the global electricity generation in 2015. The total CO₂ emissions from electricity generation in BRI

nations increases from 4232.34 Mt in 2013 to 4402.38 Mt in 2015. Figure 3 presents the 2013 and 2015 ACI values of 62 BRI nations, China, USA, EU, and the world. A green bar indicates a decrease (improvement) while a red bar an increase (deterioration) in ACI from 2013 to 2015. In Fig. 4, the reference line for plotting the bars is the 2015 ACI, i.e., the values on the left of green bars and on the right of red bars, and the countries are arranged in ascending order from top to bottom according to their ACI changes during 2013–2015. For comparisons, the ACI changes of the world, EU, and the USA are shown as the green bar at the top of the figure.

Indeed, the electricity is almost entirely generated by hydropower in the countries with a very low ACI in both years, e.g., Nepal, Ethiopia, Albania, and Tajikistan. On the other hand, countries with high ACI values in both years are generally those with a high proportion of fossil energy and low thermal generating efficiency, e.g., Mongolia, Iraq, and Estonia. Based on the 2015 data, ACI values in 42 BRI nations decrease with the average reduction of 0.04 kg/kWh and most evident reduction of 0.16 kg/kWh in Iraq, while the average rising ACI values in 23 BRI nations is 0.07 kg/kWh and the top rising is Cambodia of 0.19 kg/kWh. It is logical to suggest that countries with a very large ACI in 2013 are more likely to see large changes in their ACI between 2013 and 2015. In fact, the ACI value of some of them deteriorated but even then, the resulting 2015 value remained very low and compared favorably to those of other countries. Completely, the average ACI in all BRI nations is slightly reducing 0.0003 kg/kWh, much less than the global average reduction of 0.022 kg/kWh (IEA 2017).

Ang and Su (2016) computed the 1990 and 2013 ACI of the 124 countries. The distribution of ACI in different periods in the same countries in Ang’s study and this research is represented in Fig. 5 with 26 countries and global ACI. By contrast, the improvement margin of multiple countries ACI between 2013 and 2015 is more significant than that between 1990 and 2013, which indicates more positive performance of

Fig. 3 Regional power installation structure in BRI in 2016 (CIS is the abbreviation of Commonwealth of Independent States, a group of independent countries that were part of the Soviet Union until 1991). CEE is the abbreviation of Central and Eastern Europe. Data sources: End Coal, International Renewable Energy Agency and World Nuclear Association



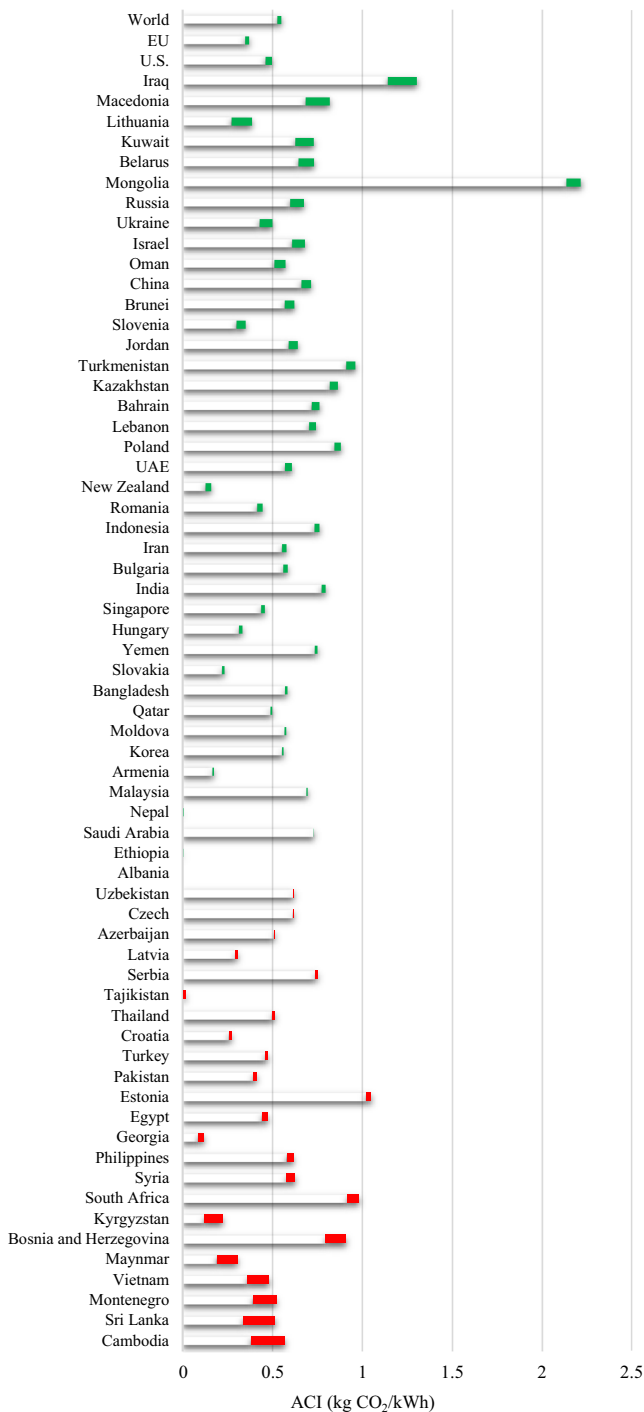


Fig. 4 ACI of electricity generation for BRI nations and other regions: 2013, 2015, and changes between the two years

carbon emission reduction in electricity generation industry between 2013 and 2015. The global ACI is in the slow process of improvement. Thereinto, the continuous improvement and deterioration of ACI are observed in 12 and 3 countries, respectively; ACI value changes from deterioration to promotion appear in five countries and the opposite performance is found in six countries. If only from the aspect of power

generation situation, these changes are generally caused by variation in the proportion of fossil generation. Not completely like this, some unexplained reasons contributing to the anomaly observed will be discussed in the following sections.

Methodology and data

The impacts of the electricity sector on the growth of carbon emissions is a complex process. To figure out the drivers of carbon emissions in electricity generation, a suitable and popular index decomposition analysis (IDA) is applied in this paper. This study chooses the primary IDA approach known as logarithmic mean Divisia index (LMDI) model. LMDI is widely applied and convincing because of its excellent characteristics, such as eliminating the incapable residual items, solving the zero-value problem in the data, simplifying the calculation process, and directly perceiving the nature of decomposition results (Ang 2004). The national carbon emissions in electricity sector can be expressed as:

$$C_j = \sum_{j,i} Q_j \cdot \frac{Q_{ij}}{Q_j} \cdot \frac{F_{ij}}{Q_{ij}} \cdot \frac{C_{ij}}{F_{ij}} \tag{1}$$

where C_j and Q_j are respectively the total CO₂ emissions from electricity production and the electricity production from fossil fuels in country j , Q_{ij} is the electricity production from fossil fuel i in country j , F_{ij} and C_{ij} are respectively the associated energy input and CO₂ emissions. The fossil fuels for power generation are considered only three categories—coal, natural gas, and petroleum.¹

The national ACI, devoted by R , is presented by:

$$R = \frac{C_j}{G_j} = \sum_{j,i} \frac{Q_j}{G_j} \cdot \frac{Q_{ij}}{Q_j} \cdot \frac{F_{ij}}{Q_{ij}} \cdot \frac{C_{ij}}{F_{ij}} = \sum_{j,i} p_j m_{ij} u_{ij} e_{ij} \tag{2}$$

where $p_j = Q_j/G_j$ is the proportion of electricity generated from fossil fuels, $m_{ij} = Q_{ij}/Q_j$ is the share of electricity generated from fossil fuel i in total electricity generation from fossil fuels, $\frac{1}{u_{ij}} = Q_{ij}/F_{ij}$ is the generation efficiency of fossil fuel i , and $e_{ij} = C_{ij}/F_{ij}$ is the emission factor for fossil fuel i which is taken as a constant in this study due to lack of further disaggregated data.

The changes in national ACI from year 0 to year T can be decomposed to

$$\Delta R = R^T - R^0 = \Delta R_p + \Delta R_m + \Delta R_u + \Delta R_e \tag{3}$$

where ΔR_p , ΔR_m , ΔR_u , and ΔR_e are respectively impacts associated with changes in p_j , m_{ij} , u_{ij} , and e_{ij} from year 0 to

¹ The electricity generated from biomass and waste is excluded but its associated carbon emissions are included when calculating the ACI.

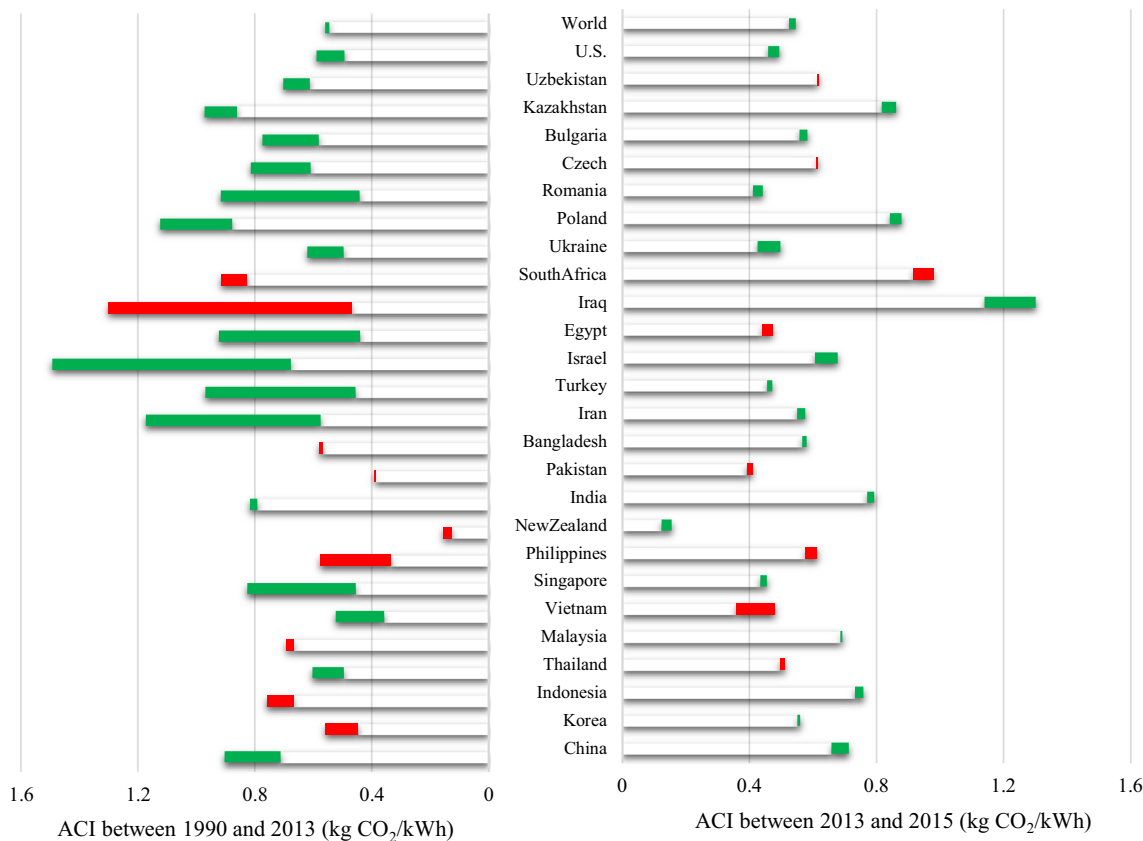


Fig. 5 Comparison of the 2013–2015 ACI and 1990–2013 ACI

year T . The meanings of these effects are as follows: the “fossil fuel share effect” (ΔR_p) represents the effect of a shift in the proportion of total electricity production from fossil fuels, the “fossil fuel mix effect” (ΔR_m) represents the effect of changes in fossil fuel mix in electricity production from fossil fuels, the “generation efficiency effect” (ΔR_u) represents the effect of changes in the reciprocal of thermal efficiency of fossil fuel generation, and the “emission factor effect” (ΔR_e) captures the effect of changes in the emission factors of fossil fuels. The emission factors are assumed to be constant over time and hence $\Delta R_e = 0$.

So, the global or regional ACI can be given by:

$$R = \frac{C}{G} = \sum_{j,i} \frac{G_j}{G} \cdot \frac{Q_j}{G_j} \cdot \frac{Q_{ij}}{Q_j} \cdot \frac{F_{ij}}{Q_{ij}} \cdot \frac{C_{ij}}{F_{ij}} = \sum_{j,i} s_j p_j m_{ij} u_{ij} e_{ij} \tag{4}$$

where C and G are respectively the global or regional total carbon emissions and generation, and s_j are the proportion of county j electricity generation to global or regional generation, and p_j , m_{ij} , u_{ij} , and e_{ij} are defined in the same way as before. Eq. (3) becomes

$$\Delta R = R^T - R^0 = \Delta R_s + \Delta R_p + \Delta R_m + \Delta R_u + \Delta R_e \tag{5}$$

Following the LMDI implementation guide in Ang (2015), the additive LMDI decomposition model is the appropriate

technique to compute the impacts. The corresponding decomposition formulae are:

$$\Delta R_s = \sum_{j,i} L(w_{ij}^T, w_{ij}^0) \ln \left(\frac{s_j^T}{s_j^0} \right) \tag{6}$$

$$\Delta R_p = \sum_{j,i} L(w_{ij}^T, w_{ij}^0) \ln \left(\frac{p_j^T}{p_j^0} \right) \tag{7}$$

$$\Delta R_m = \sum_{j,i} L(w_{ij}^T, w_{ij}^0) \ln \left(\frac{m_{ij}^T}{m_{ij}^0} \right) \tag{8}$$

$$\Delta R_u = \sum_{j,i} L(w_{ij}^T, w_{ij}^0) \ln \left(\frac{u_{ij}^T}{u_{ij}^0} \right) \tag{9}$$

$$\Delta R_e = \sum_{j,i} L(w_{ij}^T, w_{ij}^0) \ln \left(\frac{e_{ij}^T}{e_{ij}^0} \right) \tag{10}$$

where $w_{ij}^T = \frac{C_{ij}^T}{G^T}$, $w_{ij}^0 = \frac{C_{ij}^0}{G^0}$, $L(x, y) = \frac{x-y}{\ln x - \ln y}$ for $x \neq y$, and $L(x, y) = x$ for $x = y$. Thus, from our dataset, we have 2013 as year 0 and 2015 as year T .

The ACI decomposition is constructed to explain the transition. The year 2013 is chosen as the base year for common emissions level and 2015 is the corresponding year. And 62 BRI nations, China, USA, EU, and the world are included in

this study. The data is publicly available from IEA World Energy Balance Statistics Database² that involves massive and comprehensive statistical data, such as total primary energy supply (TPES), total final consumption, power generation, carbon emissions, and fossil fuels for generation.³ It should be highlighted that the carbon emissions data contains the power generation and combined heat and power, which makes the higher real carbon emissions and less generation efficiency for fossil fuels. It will eventually lead to the ACI values higher than the real levels.

Decomposition results

Regional ACI

The regional aggregate changes of ACI in electricity sector are shown in Fig. 6. China and the USA as the world's largest producers and consumers of energy are regarded as separate regions to discuss the improvements in the ACI. In the five typical regions, only the ACI value in BRI nations increases during 2013 and 2015, and the ACIs in China, USA, EU, and the world maintain the downward trend. EU countries have been devoting to reduce carbon emissions. Karmellos et al. (2016) analyzed that the level of CO₂ emissions in EU-28 decreased by almost 10% from 2007 to 2012 primarily due to the fuel mix changes. The ACI in China appears to a remarkable reduction through the rapid development of renewable energy and the significant role of clean and efficient transition of coal power. The renewable energy installed capacity was developing with a rapid growth from 358 GW in 2013 to 479 GW in 2015 while the thermal power installed capacity proportion gradually decreased because of new installed thermal power proportion shrinks and small-scale shutdown. It is significant that the proportion of thermal generation declined from 78.58% in 2013 to 71.85% in 2015. Besides, with the improvement of the efficiency of thermal power generation, the carbon dioxide emission intensity of thermal power in China decreased from 855 g/kWh in 2013 to 850 g/kWh in 2015 reported by China Electricity Council (CEC 2017). Yuan et al. (2014b) predicted that CO₂ emissions will peak at 9200–9400 Mt in 2030–2035 in China, while it can be potentially reduced by 200–300 Mt. Ji et al. (2018) estimated China's natural gas demand would reach 340 bcm and 528 bcm in 2020 and 2030 in the Business as Usual (BAU) scenario, respectively. It is worth mentioning that the investment enthusiasm on coal power remains unabated and leads to continuous operation efficiency deterioration after 2015, with the

reasonable capacity addition space of coal power ranging between 50 GW and 100 GW during 2016–2020 (Yuan et al. 2016).

The primary impacting factor in the ACI is the geographical shift effect (ΔR_s), which is the determining factor especially in China and BRI regions. Specifically, China has been the largest contributor to the geographical shift effect. And the rapid growth of economy and power demand in BRI nations contributes to the geographical shift effect then to increase ACI value, whereas the geographical shift effect is remission improvement for China, USA, and EU. It can be inferred that the BRI nations are switching from energy suppliers to consumers and increasingly impacting the global energy landscape with the proportion of electricity generation increasing from 27.6% to 28.5%. The global revolution of energy transition from dominant thermal power to renewable energy extension is performing a positive effect (ΔR_p) on the ACI reduction, while the BRI regions assembling many emerging economies will sustain the fossil-based energy. The positive effect of improvements to the fuel mix (ΔR_m) is particularly evident in the USA because gas power generation is replacing the traditional coal power and contributing the reduction of carbon intensity of thermal power. Benefiting from the technological progress and policy support, the power generation efficiency (ΔR_u) is improving with steady steps, which is remarkable in the developing countries of China and BRI regions.

Due to the geographical shift effect, the observed reduction in regional ACI values has a great deviation from the “real performance” estimated at the national level. Since the developing countries have high potential for growth in electricity demand, whereas most OECD countries where growth in electricity demand is expected to be much lower are found, it can be expected that the geographical shift effect observed will continue for a period of time (Ang and Su 2016). Though the ACIs for electricity generation are notable decreasing in China, USA, and EU countries, many developing countries may rise against the tide because of the pressing need for economic development. Without financial and technical support from the global community, it will be very rough and endless for emerging economies to embark on a sustainable development pathway. This means that to reduce the global ACI and emissions, extra effort must be made by all countries to achieve improvements through the three “real performance”-related effects, i.e., reducing fossil fuel share, switching to cleaner fossil fuels, and improving generation efficiency.

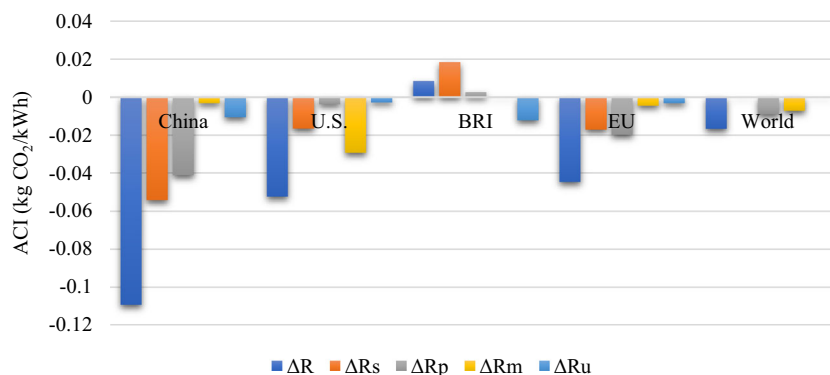
National ACI

The individual national ACI changes in BRI regions are shown in Fig. 7 where the countries are arranged in descending order (the increasing ACI values are positive and the

² IEA World Energy Balance Statistics Database (<<https://www.iea.org/statistics/>>).

³ The fossil fuel mix contains only coal (anthracite, coking coal, lignite, other bituminous coal, and sub-bituminous coal), natural gas, and petroleum (crude oil, diesel oil and fuel oil).

Fig. 6 Decomposition of global change in ACI between 2013 and 2015. According to IEA (2017), global ACI decreased from 0.547 g/kWh to 0.525 g/kWh during 2013 and 2015. The differences between the IEA estimates and our estimates arise from the CO₂ emissions associated with biomass and waste. However, the vital information of these two estimates convey is the same



decreasing ACI values are negative). There is a discrepancy between decomposition results and real values of ACI changes. This is caused by the calculation process without considering biomass fuel power generation and some statistical errors, but it remains an important reference for the carbon reduction in electricity sector.

Albania and Ethiopia are typical countries where the renewable energy completely undertakes the responsibility for power supply, so its ACI for electricity generation is always zero. In Fig. 7, Albania is considered the national demarcation for ACI increasing and reducing. According to the results obtained, the countries can be approximately divided into three groups: (1) group with ACI and almost three effects decreasing (including Lithuania, Kuwait, Kazakhstan, Belarus, Oman, Israel, Jordan, China, Russia, Slovenia, Turkmenistan, Brunei, United Arab Emirates (UAE), Bahrain, Poland, New Zealand, USA, Romania, Hungary, Singapore, Yemen, Qatar, Nepal, and Ethiopia); (2) group with ACI and almost three effects increasing (including Cambodia, Vietnam, Bosnia and Herzegovina, Myanmar, Philippines, Georgia, Egypt, and Thailand); (3) group with certain dominant change factor (including the rest of the country).

For group 1, the power generation efficiency (ΔR_u) is the most significant factor for ACI reduction and other two effects also offer positive contributions. Goh et al. (2018) confirmed that the most consistent contributor to a reduction in the ACI is the improvement in power generation efficiency. Nearly all group 1 countries are dominant by fossil power, e.g., gas power generation for Kuwait, Oman, UAE, and Qatar, and traditional coal power generation for China and Poland. As reported, from the carbon intensity perspective, Poland's carbon emissions per euro of GDP in 2015 was 923.6 gce, and compared with 2010 (1128.8 gce/euro), an average annual decline of 41.1 gce/euro is the most remarkable improvement in European countries (Gogan et al. 2017). However, the share of coal power is still up to 79% (48% from lignite firing and 31% from anthracite) in Poland with the highest proportion of fossil power generation in 2017. "Poland Energy Planning 2040" (PEP 2040) announces that the electricity demand will

be 231.8 TWh, of which coal power, wind, nuclear, gas power, solar, and hydro and biomass accounts for 32%, 19%, 18%, 16%, 8%, and 7%, respectively. This will be an arduous and long process. In the case of difficult process of energy structure transition, promoting power generation efficiency contributes to reduce the cost of power generation and carbon emissions, which is also the most powerful pathway for developing countries to provide sustainable and affordable electricity access.

As to group 2, all three effects tend to contribute to an increase in ACI with the rise in fossil fuel share in total power generation and a slight drop in power generation efficiency. Five of these countries are in Southeast Asia where the hot investment of coal power is concentrated. To be precise, the planning installed capacity of coal power in Southeast Asia has accumulated about 110.5 GW accounting for 16.8% of global coal power planning capacity. The inefficiency of small-capacity coal power plants in these countries will deteriorate with the extension of service time. Thereby the fossil fuel mix and power generation efficiency are attributable to raise the ACI. Zhao et al. (2018) estimated that the average of total factors energy efficiency was 0.537 in 35 BRI nations in 2015 and insisted that it was cautious to make the energy technology options, development planning, and regulation in BRI nations. There is a detailed description. By 2016, the total installed capacity in Vietnam has reached 42.44 GW, of which the installed capacity of hydropower, gas, and coal-fired power is 17.5 GW (41.2%), 7.5 GW (17.7%), and 14.44 GW (34%), respectively. Although the development of non-hydro power installation is insufficient, the power source structure is relatively reasonable. Vietnam has set a relatively ambitious renewable energy development targets and has recently introduced a short-term FIT tariff policy (2017–2019). But since 2010, only a limited number of the renewable energy projects have been launched in the technology demonstration stage. The rapid expansion of Vietnam's coal power increasing from 3.69 GW in 2010 to 14.44 GW in 2016 is supported mainly by overseas financing from China, Japan, and South Korea. But the operating coal-fired power plants are generally poor in generation efficiency (only 29.5% in 2015) and pollutant

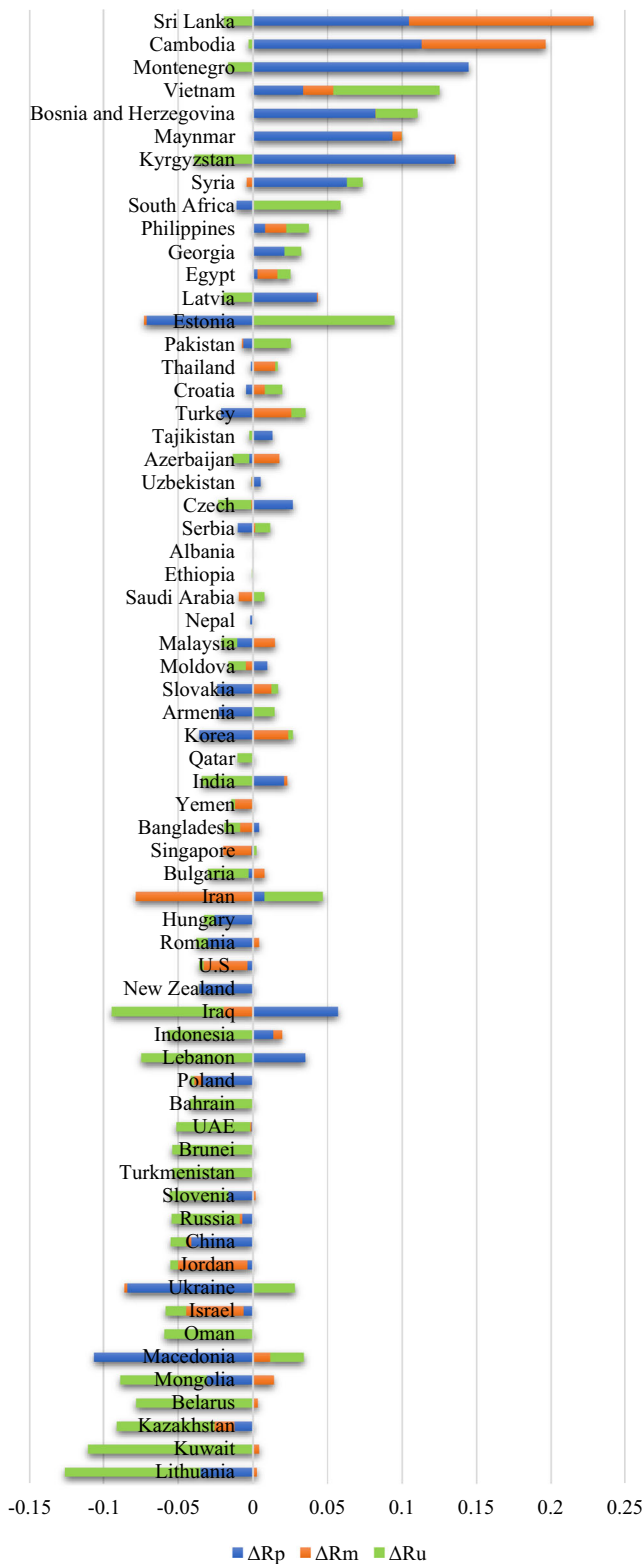


Fig. 7 Decomposition results of ACI in BRI nations from 2013 to 2015

control standards, as well as crowding out the renewable energy, which may lead Vietnam to lose opportunities to participate in the innovation and upgrading of global energy

technology. It suggests Vietnam to focus on optimizing the power supply structure on the bases of improvement of power supply capacity, to accelerate the development of renewable energy within the scope of an acceptable additional cost, to improve the safety and sustainability of energy supply, and to avoid unnecessary risks of energy security and carbon lock-in.

For group 3, the influence of three effects presents different and confused routes varying among countries. For example, the fossil fuel share is the main contributor to a decrease in ACI in Macedonia, Ukraine, Korea, Armenia, and Slovakia; the fuel mix effect is the same to Iran and Saudi Arabia; and the power generation efficiency is the significant improvement for ACI reduction in Lebanon, Indonesia, Iraq, Bulgaria, and Moldova; especially, the ACI reduction in Malaysia is due to both the fossil fuel share and power generation efficiency effect. As to the countries with increasing ACI, the performance of three effects is consistent with the previous illustration. Indonesia’s rapid economic growth, coupled with the expansion of population and the improvement of electrification, is driving up its electricity demand over the medium to long term and pushes the Indonesian government to update the power development plan every year. Indonesia’s “Electricity Supply Business Plan 2018–2027”, approved in March 2018, announced that the total capacity of power plant development is 56,024 MW and the coal power target of end energy mix by 2025 is 54.4%, indicating the coal power capacity would be 55 GW. It is encouraging that the generation efficiency of coal power increases from 31.2% in 2010 to 35.7% in 2015, which is the top contributor to the ACI reduction. Indonesia’s power planning determines that coal will be the main source of power supply for a long time in the future. To meet the dual goals of economic growth and constraints of environmental protection, the construction of coal power plants must achieve the goals of economic operation as well as improve technical standards for the entry of new coal-fired power units. Under the pressures of global low-carbon transition, fulfilling NDC commitment, environmental protection requirements, and economic return, Indonesia’s coal power is bound to move toward a clean and efficient development. Although it will increase investment burden in the power industry and the cost of power generation and potentially reduce the rate of return in power investment projects, it will also avoid the huge waste caused by low efficient and inefficient investment in the process of low-carbon transition, transcending the old development path of “governance after pollution” in the industrialization process of early industrialized countries. These lay a strong foundation for improving the future development efficiency.

Overall, the improvements in thermal power generation efficiency are highlighted in ACI reduction by summarizing the critical drivers in BRI nations. In certain countries with negative generation efficiency effect, the coal power efficiency decreases obviously in Vietnam, Estonia, South Africa,

Ukraine, and Macedonia; the gas power efficiency decreases in Armenia and Iran; and the petroleum generation efficiency decreases rapidly in Pakistan. In these special national circumstances, thermal power will sustain the dominant status, which means the fossil fuel share and fuel mix likely making negative impacts and even causing a further decline of generation efficiency with the disorganized growth of thermal power installation. Thereby, the efficient measures to reduce ACI are to improve the generation efficiency of newly built units and gradually eliminate lagging plants.

Conclusion and policy implications

Emerging economies have already become the pillar force of global economy and trade while at the same time are enduring financial, technological, management, and talent problems during the development process. For the BRI nations, their electricity industry can hardly achieve the dual tasks of providing adequate power supply and reducing carbon emissions. Fortunately, the world has made a step forward in establishing multilateral climate governance, but the actual progress is anything but substantial due to insufficient moves, as suggested by the geographical shift effect in BRI regions.

There have been more than 60 BRI countries submitting the NDC to the United Nations Framework Convention on Climate Change (UNFCCC). To promote the performance of carbon emission reduction, bilateral and multilateral arrangements for financial, technological, and infrastructure building are the essential options. The “Belt and Road Initiative” is a comprehensive and multi-level cooperation concept to aggregate the existing bilateral channels and regional frameworks, which is different from the bottom-up or top-down agreements. In this process, China can take the leadership in green development by deploying advanced power technology, rich financial resources, and strong engineering capability.

Several developed countries have already started to design power markets that can facilitate investment in decarbonization. The central objectives include pricing in externalities, enabling returns on capital-intensive technologies (wind and solar), overcoming the lock-in of existing high-carbon generation, and in addition, the need to ensure operational efficiency while also securing sufficient investment in flexible resources (demand-side resource and energy storage) (IEA 2016b). Renewable energy has been recognized as low-carbon, clean, and sustainable power resource, and the violent expansion in the global energy sector is witnessed. Nevertheless, the intermittency and unpredictability nature of renewable energy makes large-scale deployment a huge challenge while high cost is another barrier (Stram 2016). Thus, to date, in BRI countries, the substitution of renewables to traditional fossil fuel in the fuel mix only happens in

countries with an adequate power sector, including China, South Korea, and some European countries.

The BRI developing countries should pay great attention to improve generation efficiency in existing fleet, in particular coal-fired plants (Malla 2009). Wang et al. (2017) revealed that sectoral emission efficiency improvement was the main contributor to the slight decrease in global emission intensity during 2000–2009. For BRI power cooperation, enhancing energy efficiency should be the priority of green power development pathway. Retrofit of existing units is the most important option while new build must follow strict standards in energy efficiency and pollutant control. Affordable renewable energy is an alternative way to mitigate carbon emissions.

As a matter of fact, China has participated in 240 coal power projects with a total installed capacity of 251 GW in 25 BRI nations by 2016 (Ren et al. 2017), which portends remarkable achievements in BRI power cooperation despite with controversy on carbon leakage. Considering the big gap of generation efficiency between China (40.3%) and other BRI countries (e.g., Indonesia, 32.3%; Vietnam, 24.6%; and Pakistan, 21.3% in 2016), such a cooperation could facilitate energy efficiency improvement by deploying China’s advanced coal power technology. The potential of energy saving and carbon emissions reduction for BRI nations is very big (Zhao et al. 2018; Zhang et al. 2018). However, a balance should be maintained to the high environmental risk of fossil energy investment along the BRI (Duan et al. 2018).

Furthermore, China has already become the largest and fastest growing market for renewable energy in the world. China ranked in the first position in terms of cumulative wind capacity installation and China’s five wind power companies contributed about 28% in global wind turbine manufacturing market by the end of 2016 (REN21 2017). In the photovoltaic industry, with strong supporting policy, learning by development, and learning by doing, the efficiency of PV generation is improving quickly. For example, the conversion efficiency of monocrystalline and polysilicon are 20.6% and 18.6% in 2017. During 2002–2011, China’s enterprises made at least 124 investments in solar and wind energy industries in 33 countries, totaling in nearly \$40 billion (WRI 2013). Furthermore, a recent report remarked that China’s overseas new energy investment increased to \$32 billion and \$44 billion in 2016 and 2017, respectively (IEEFA 2018). The Belt and Road Initiative can certainly accelerate the development of efficient and low-carbon power industry under the premise of ensuring sufficient power supply capacity. This sentiment is echoed in a recent study by Li et al. (2018a, b), which explored China’s essential contributions to global green energy and low-carbon development via Belt and Road Initiative.

Acknowledgments The authors acknowledge the funding of National Natural Science Foundation of China (71673085), the Fundamental Research Funds for the Central Universities (2018ZD14), Beijing

Social Science Fund (16YJB027), and the 111 Project (B18021). The authors would also like to acknowledge great thanks to anonymous reviewers for their valuable comments which largely improve the academic quality of this paper. The usual caveats apply.

Compliance with ethical standards

Conflicts of interest The authors declare no conflict of interest.

References

- Ang BW (2004) Decomposition analysis for policymaking in energy: which is the preferred method? *Energy Policy* 32(9):1131–1139
- Ang BW (2015) LMDI decomposition approach: a guide for implementation. *Energy Policy* 86:233–238
- Ang BW, Su B (2016) Carbon emission intensity in electricity production: a global analysis. *Energy Policy* 94:56–63
- Ang BW, Zhou P, Tay LP (2011) Potential for reducing global carbon emissions from electricity production—a benchmarking analysis. *Energy Policy* 39:2482–2489
- CEC (2017) Report on clean development of coal power in China, Beijing
- Dai S, Zhang M, Huang W (2016) Decomposing the decoupling of CO₂ emission from economic growth in BRICS countries. *Nat Hazards* 84(2):1055–1073
- Duan F, Ji Q, Liu B, Fan Y (2018) Energy investment risk assessment for nations along China's Belt & Road Initiative. *J Clean Prod* 170:535–547
- Ersin K, Alper A, Bayram D, Mustafa K (2016) Hierarchical structure of the countries based on electricity consumption and economic growth. *Phys A Stat Mech Appl* 454:1–10
- Fei L, Dong S, Xue L, Liang Q, Yang W (2011) Energy consumption-economic growth relationship and carbon dioxide emissions in China. *Energy Policy* 39(2):568–574
- Gogan K, Partanen R, Denk W (2017) European Climate Leadership Report 2017. *Energy For Humanity*
- Goh T, Ang BW, Su B, Wang H (2018) Drivers of stagnating global carbon intensity of electricity and the way forward. *Energy Policy* 113:149–156
- Hamit-Hagggar M (2012) Greenhouse gas emissions, energy consumption and economic growth: a panel cointegration analysis from Canadian industrial sector perspective. *Energy Econ* 34(1):358–364
- Han L, Han B, Shi X, Su B, Lv X, Lei X (2018) Energy efficiency convergence across countries in the context of China's belt and road initiative. *Appl Energy* 213:112–122
- IEA (2016a) World energy outlook 2016. International Energy Agency, Paris
- IEA (2016b) Re-powering markets: market design and regulation during the transition to low-carbon power systems. International Energy Agency, Paris
- IEA (2017) CO₂ emissions from fuel combustion. International Energy Agency, Paris
- IEA (2018) IEA world energy balances 2018. International Energy Agency, Paris
- IEEFA (2018) China 2017 review: World's second-biggest economy continues to drive global trends in energy investment. Institute for Energy Economics and Financial Analysis, Cleveland
- Ji Q, Fan Y, Troilo M, Ripple RD, Feng L (2018) China's natural gas demand projections and supply capacity analysis in 2030. *Energy J* 39(6):53–70
- Ji Q, Xia T, Liu F, Xu J (2019) The information spillover between carbon price and power sector returns: evidence from the major European electricity companies. *J Clean Prod* 2018:1178–1187
- Kais S, Sami H (2016) An econometric study of the impact of economic growth and energy use on carbon emissions: panel data evidence from fifty-eight countries. *Renew Sust Energ Rev* 59:1101–1110
- Karmellos M, Kopidou D, Diakoulaki D (2016) A decomposition analysis of the driving factors of CO₂ (carbon dioxide) emissions from the power sector in the European Union countries. *Energy* 94:680–692
- Li H, Li F, Yu X (2018a) China's contributions to global green energy and low-carbon development: empirical evidence under the belt and road framework. *Energies* 11
- Li X, Liao H, Du Y, Wang C, Wang J, Liu Y (2018b) Carbon dioxide emissions from the electricity sector in major countries: a decomposition analysis. *Environ Sci Pollut Res* 25(7):6814–6825
- Liu Y, Hao Y (2018) The dynamic links between CO₂ emissions, energy consumption and economic development in the countries along “the belt and road”. *Sci Total Environ* 645:674–683
- Madaleno M, Moutinho V (2017) A new LDMI decomposition approach to explain emission development in the EU: individual and set contribution. *Environ Sci Pollut Res* 24(11):10234–10257
- Malla S (2009) CO₂ emissions from electricity generation in seven Asia-Pacific and North American countries: a decomposition analysis. *Energy Policy* 37:1–9
- Niu S, Ding Y, Niu Y, Li Y, Luo G (2011) Economic growth, energy conservation and emissions reduction: a comparative analysis based on panel data for 8 Asian-Pacific countries. *Energy Policy* 39(4):2121–2131
- Ozcan B (2013) The nexus between carbon emissions, energy consumption and economic growth in Middle East countries: a panel data analysis. *Energy Policy* 62:1138–1147
- Peng J, Xie R, Lai M (2018) Energy-related CO₂ emissions in the China's iron and steel industry: a global supply chain analysis. *Resour Conserv Recycl* 129:392–401
- Ren P, Liu C, Zhang L (2017) Survey of China's participation in coal generation projects in BRI nations. Global Environment Institute, Beijing (in Chinese)
- REN21 (2017) Renewable 2017 Global Status Report. Renewable Energy Policy Network for the 21st Century, Paris
- State Council (2015) Vision and proposed actions outlined on jointly building silk road economic belt and 21st-century maritime silk road. State Council, Beijing (in Chinese)
- Stram BN (2016) Key challenges to expanding renewable energy. *Energy Policy* 96:728–734
- Sun C, Ding D, Yang M (2017) Estimating the complete CO₂ emissions and the carbon intensity in India: from the carbon transfer perspective. *Energy Policy* 109:418–427
- Tang X, Jin Y, Wong X et al (2017) Will China's trade restructuring reduce CO₂ emissions embodied in international exports? *J Clean Prod* 161:1094–1103
- Wang H, Ang BW, Su B (2017) A multi-region structural decomposition analysis of global CO₂ emission intensity. *Ecol Econ* 142:163–176
- WDI (2018) World Bank Data Indicator. <http://data.worldbank.org/indicator>
- WRI (2013) China's foreign investment in wind and solar energy industry: trends and motivations. World Resource Institute, Washington, DC
- Yan Q, Zhang Q, Zou X (2016) Decomposition analysis of carbon dioxide emissions in China's regional thermal electricity generation, 2000–2020. *Energy* 112:788–794
- Yu S, Hu X, Fan J, Cheng J (2018) Convergence of carbon emissions intensity across Chinese industrial sectors. *J Clean Prod* 194:179–192
- Yuan JH, Xu Y, Zhang XP (2014a) Income growth, energy consumption, and carbon emissions: the case of China. *Emerg Mark Financ Trade* 50(5):169–181
- Yuan JH, Xu Y, Hu Z, Zhao C, Xiong M, Guo J (2014b) Peak energy consumption and CO₂ emissions in China. *Energy Policy* 68(2):508–523

- Yuan JH, Li P, Wang Y, Liu Q, Shen X, Zhang K, Dong L (2016) Coal power overcapacity and investment bubble in China during 2015–2020. *Energy Policy* 97:136–144
- Yuan JH, Zhao CH, Zhang HN (2018) Research on the green power cooperation. North China Electric Power University, Beijing (in Chinese)
- Zhang Y, Jin Y, Shen B (2018) Measuring the energy saving and CO₂ emissions reduction potential under China's belt and road initiative. *Comput Econ* in press
- Zhao CH, Zhang HN, Zeng YR et al (2018) Total-factor energy efficiency in BRI nations: an estimation based on three-stage DEA model. *Sustainability* 10(1)

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.