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Electric power development associated with the Belt and Road Initiative and its carbon emissions implications

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HIGHLIGHTS

- We examine 458 power plants built since 2005 in 15 representative BRI countries.
- Fossil fuel power generation accounts for 75% of capacity addition.
- The number of solar PV and wind projects is increasing but capacity remains small.
- Estimated committed CO_2 emissions are 56 (40–72) Gt by 2030.
- This corresponds to 7–17% of the remaining carbon budget for 1.5 °C climate goal.

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ABSTRACT

The Belt and Road Initiative (BRI), initially proposed by China in Fall 2013, involves large-scale development of infrastructure, including energy infrastructure, in Asia, Europe, and Africa, and thus has the potential to affect global climate. In this work, we analyze publicly available information for 458 power plant development projects in 15 representative countries across the BRI regions from eight years prior to BRI (January 2005), to 6 years after BRI (June 2019) in which Chinese engineering contracting companies played a significant role. The data indicate that coal, gas, and solar photovoltaics (PV) activities increased to different degrees after BRI was introduced. We find that 75% of the new generation capacity after October 2013 has gone to fossil fuels, while the rest has gone to hydroelectricity (14%), solar PV (6%), wind (3%), and others (2%). Those numbers have important carbon emissions implications. Based on current trends, the total BRI-associated power development in the 15 countries could generate 37 (range 26–48) gigatonnes (Gt) of committed carbon dioxide (CO_2) emissions by the end of 2030, corresponding to 4–11% of the remaining carbon budget for the 1.5-degree climate goal. Extrapolation of these results to all BRI countries gives an estimate of 56 (range 40–72) Gt CO_2 for cumulative BRI-related committed emissions by 2030, corresponding to 7% to 17% of the remaining 1.5-degree carbon budget. If the projected growth of fossil fuel power generation in BRI slows down prior to 2030, there are commensurate reductions in emissions implications. To provide context for these numbers, we define a "greenness ratio," which can be used to measure the level of environmental sustainability of BRI in the power sector.

1. Introduction

The Belt and Road Initiative (BRI), also known as the "One Belt, One Road" initiative, was introduced in September-October 2013 by China as a vision to promote connectivity and economic integration among, but not limited to, countries in Asia, Europe, and Africa. It has two major components: the land-based "Silk Road Economic Belt," which spans all of Asia, Russia, the Baltic region, the Mediterranean region, the Middle East, and the Indian Ocean, and the ocean-based "21st-century Maritime Silk Road," which connects the ports in East China to the Indian Ocean, Europe, and the South Pacific Ocean through the South China Sea [1]. The scale of the BRI is vast. China's state-owned Silk Fund, which provides financial support for the BRI, has a total capital of 40 billion U.S. dollars (USD) plus 100 billion Chinese yuan (CNY) [2]. China's two policy banks, the China Development Bank (CDB) and the Export-Import Bank of China (CHEXIM), have committed

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250 billion CNY and 130 billion CNY, respectively, to provide loans for BRI-related cooperation [3]. By April 2019, 132 countries had signed BRI-related cooperation agreements with China [4]. These 132 countries, which do not include India, are referred to as “BRI countries” in this paper with the complete list shown in Table S1 of the Supporting Information (SI). Note that we do not include China in the BRI list.

The large amount and variety of infrastructure development projects associated with the BRI means it could have substantial influence on the energy development in a large part of the world and have profound associated impacts on Earth’s environment and climate, as pointed out and discussed by Zhang et al. and Ascensão et al. [5,6]. In this work, we focus on the development of electric power sector (i.e., electricity and heat generation) in the BRI regions rather than others such as the transportation or the building sector because (1) Asia and Africa are projected to have increases in primary energy consumption higher than any other regions over the next three decades [7,8]; (2) the electric power sector is a large carbon dioxide (CO_2) emitter, accounting for 42% of global CO_2 emissions from fuel combustion in 2016 [9]; and (3) the fossil fuel-based power generation systems developed today would lock in CO_2 emissions for at least the next few decades.

As a relatively new topic, energy development in the BRI regions associated with China is covered mainly by institutional reports and tracked by databases, oftentimes as the byproduct of studies on China’s overseas investments. Zhou et al. (2018) reviewed loans (i.e., debt investments) provided by Chinese banks and equity investments from the Silk Fund and Chinese non-financial enterprises to 56 BRI countries’ energy and transportation sectors from 2014 to 2017 and found that the deals did not align well with the low-carbon priorities stated in those BRI countries’ Nationally Determined Contributions [10]. Peng et al. analyzed Chinese involvement in more than 200 coal-fired power projects in 24 BRI countries and India from 2001 to 2016 and showed that project contracting is the major form of participation, followed by equipment exportation, equity investments, and bank loans [11]. However, that report only presents results in the aggregate form. Shearer et al. looked at committed and proposed Chinese financing of coal-fired capacity under development as of July 2018 in 27 countries, including 23 BRI countries, and summarized the primary investors in category of policy banks, commercial banks, and non-financial enterprises and the kinds of coal technology (ultra-supercritical, supercritical, or subcritical plants) involved in the new coal-fired capacity [12]. Li et al. analyzed China’s overseas equity investments in the electric power sector from 2000 to 2017 and showed the aggregate investment portfolio in BRI countries in the unit of power generation capacity [13]. Hannam et al. stressed the importance of a global climate finance regime that incentivizes decarbonization in developing countries and, in a separate analysis, estimated the power capacity outside China involving Chinese project contracting and equipment exportation [14]. Gallagher and Qi reviewed Chinese policymaking government agencies and evaluated the policies governing China’s overseas investments from the perspective of environmental implications [15].

The China Global Energy Finance database compiled by Boston University tracks loans from CDB and CHEXIM to global energy sector, including the power generation sector, since 2000 [16]. Information including the location, borrower, lender, energy source, and amount of financing of each qualified project is displayed, and the database is updated annually. The China Global Investment Tracker published by the American Enterprise Institute covers China’s global equity investment and construction transactions across different sectors since 2005, although with limited details for each transaction [17]. The Global Coal Finance Tracker, published by Global Energy Monitor, tracks financial support (mainly from banks) of global coal-fired power plant projects since 2013 [18]. The Global Coal Plant Tracker, also from Global Energy Monitor, provides information on worldwide coal-fired power plants of various development stages including the owner of each plant [19]. The Platts World Electric Power Plant Database contains information on global power generating units including capacity, fuel type, geographic location, commission year, owner, construction contractor, and key equipment manufacturer [20]. Other worldwide power plant databases include the Global Power Emissions Database (GPED) developed by Tsinghua University and the newly-launched open-source Global Power Plant Database by World Resources Institute [21,22].

The current literature mainly examines development of the electric power sector in BRI countries from the financing perspective because adequate funding is necessary to complete a project. However, funding itself is insufficient for a power plant to be built—engineering contracting companies that provide site surveying, plant design, construction, procurement, installation, commissioning, and project management services are also necessary. Given the large financial investments, the scale of engineering contracting business is commensurately large in the BRI regions. In 2017, the total value of newly signed construction contracts by Chinese firms in the BRI countries amounted to 144 billion USD, of which 30.4 billion USD falls in the electric power sector [23]. The vital role of engineering contracting companies in the power development in BRI countries, and the lack of analysis of their role in the existing literature, motivates us to focus on engineering or construction contracts involving Chinese contractors in BRI regions. The focus on construction companies that are actually building the power plants, instead of the investors that only provide funding, also gives insights into whether Chinese domestic power industries, including fossil fuel and renewables, are being exported to the BRI regions as domestic energy policies evolve within China. This is especially important because the kinds of power development within China as well as along the BRI regions can largely determine the fate of climate change mitigation efforts. We note that, in general, an engineering contracting company earns revenue by providing services after winning the bid from a competitive bidding process initiated by the project owner, and it does not share the revenue from running the facility. Also note that in the following, we use “engineering” and “construction” interchangeably; we also use “contracting companies” and “contractors” interchangeably.

In this paper, we analyze publicly available information for 458 power plant development projects in 15 representative countries across the BRI regions in which Chinese engineering contractors play a significant role. The time period for this analysis – between January 2005 and June 2019 – provides information on activities both before and after initiation of the BRI and allows us to assess how the creation of BRI may have impacted activities in the BRI countries. We track the contract-signing date for each of the 458 power plant projects and show the time series for all 15 countries aggregately as well as individually. This kind of detailed analysis in individual BRI countries, which is absent from the current literature, enables us to examine the unique situations in each country and explore the possible drivers of the change in project type with time. Moreover, we extrapolate the post-BRI growth trend of total added capacity through 2030 and quantitatively estimate the carbon emissions implications of BRI power development in terms of committed CO_2 emissions.

Although we do not investigate the funding sources of those 458 power plants, we note that Chinese construction contractors were involved in 81% of the 59 power plant projects financed by CDB and CHEXIM in these 15 countries since year 2000, as tracked by the China Global Energy Finance database [16]. Similarly, Chinese contractors were involved in 18 of the 27 newly-built power plants with different degrees of Chinese ownership in these 15 countries, as tracked by Li et al. [13], and in all of the 8 coal-fired power plant projects marked by the Global Coal Finance Tracker [18] as having support from Chinese financial institutions. Because our dataset is likely to include a large portion of the projects financed, at least in part, by Chinese banks and non-financial enterprises, the analysis in this paper not only supplements the current literature, but also provides a more comprehensive picture of Chinese companies’ involvement in the development of the electric power sector of the BRI regions, as compared to the current literature.

We begin the presentation by reviewing the current status of electricity generation in the world by fuel sources and the importance of energy development in the BRI regions. We then describe the data collection and verification process and the associated definitions, assumptions, and limitations in detail. After that, we present and discuss results of the analysis in multiple aspects. Finally, we discuss the policy implications of this work.

2. Background

In 2017, 25,551 terawatt-hours (TWh) of electricity were generated around the globe [24]. Sixty-five percent of the total was generated from fossil fuels (38% from coal, 23% from natural gas, and 4% from petroleum), 10% was generated by nuclear energy, 16% was generated from hydroelectric, and 9% was generated from other renewables [24]. Fuel sources for electricity generation vary geographically and are summarized in Table S2 in the SI. In the future, renewables are expected to generate a higher percentage of power throughout the world [8,25]. In the United States, electricity generation from natural gas and renewables is projected to increase, and the shares of nuclear and coal generation will decrease [8,26]. China is building up large renewable and nuclear power generation capacities [7,8]. Southeast Asia will produce more electricity and is projected to have higher percentage of power generated from coal and renewables, with less from natural gas and oil [8,27].

The 132 BRI countries collectively account for 42% of world population [28]. However, they only include 19 developed economies, and 94 of the 132 countries' per capita GDP is below the world's average [29,30]. Nevertheless, the average annual GDP growth rate of these 132 countries is 9% higher than the world's average [31]. Large population, low level of economic development, and high growth rates are likely to mean high energy demand in the future. At the same time, BRI countries are vulnerable to global climate change. Countries such as Fiji, Maldives, and Bangladesh are extremely vulnerable to climate change hazards such as sea level rise, droughts, and floods [32,33]. In addition, countries such as Saudi Arabia, Russia, and Iran have the world's largest amount of proven fossil fuel reserves, and will suffer potentially huge economic losses if significant portions of those assets need to be stranded to meet climate goals [34]. For these and other reasons, it is important to consider climate change implications when developing energy infrastructure in the BRI regions.

Considerations of climate change are consistently included in the official documents of BRI. The founding BRI document, titled *Vision and Actions on Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road*, published in 2015, promoted low-carbon infrastructure construction and encouraged the participants of BRI to advance cooperation in renewable energy development and in tackling climate change [1]. The overarching guidance on energy cooperation in the BRI, named *Vision and Actions on Energy Cooperation in Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road*, published in 2017, stated that the BRI would implement the Paris Agreement on climate change, promote clean energy investment, and strive for greater energy efficiency [35]. The first and second Belt and Road Forums for International Cooperation, which took place in Beijing in 2017 and 2019, respectively, both produced joint statements that encouraged all participating parties to fully implement the Paris Agreement and to push forward cooperation in advancing renewable energy and energy efficiency [36,37].

3. Materials and methods

3.1. The 15 representative BRI countries

In this paper, we focus our analysis on 15 BRI countries and assume they represent a broader range of countries in the BRI regions. The 15 countries are: Indonesia, Malaysia, and Vietnam from Southeast Asia; Kazakhstan, Pakistan, and Uzbekistan from Central Asia; Iran, Saudi Arabia, and United Arab Emirates (UAE) from the Middle East; Egypt, Kenya, and South Africa from Africa; and Russia, Serbia, and Ukraine from Eastern Europe (see Fig. 1). These five regions are the major geographic components of the BRI activities. Also, heads of state or government from 11 of the 15 countries attended the first or second Belt and Road Forum in 2017 and 2019, respectively [39,40]. This means their governments were seriously considering, and have a continued interest in, participation in the BRI. Moreover, 14 of the 15 countries (except Uzbekistan) are among the top 20 in Asia, Africa, and

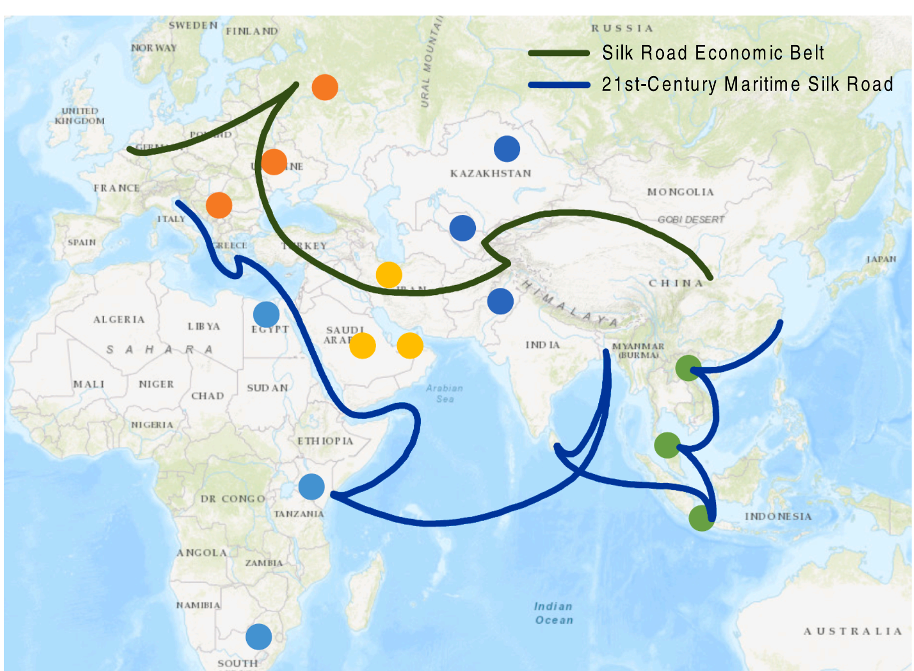

Fig. 1. A geographic illustration of the Belt and Road Initiative and the 15 representative BRI countries in this paper. The illustration is inspired by a publication from Council on Foreign Relations [38].

Europe, respectively, when ranking the total value of new construction contracts signed by Chinese firms in 2017 [23]. This indicates existing active cooperation between Chinese firms and those countries in various sectors, and makes these countries early participants in BRI and therefore representative indicators of how future activities in other BRI countries are likely to develop.

3.2. Data collection and verification

In this work, we collect information for individual power plant projects from credible internet sources. This approach is sometimes referred to as a "bottom-up" approach, and is distinct from the "top-down" analysis done by Hannam et al., which was based on company-level information from the existing Platts database [14]. Li et al. and Hannam et al. [13,14] pointed out that the Platts database has less comprehensive coverage of renewable power plants, especially solar power plants, than non-renewable plants. Also, the database only provides information on a power plant's commission year, which can be years behind the more indicative construction contract-signing date. Therefore, we chose to use the bottom-up approach to compile a more refined dataset, which enables a more accurate and nuanced analysis in the BRI regions. The authors of The China Global Energy Finance database and Peng et al. used bottom-up approaches similar to ours, with different procedures of project identification [11,16]. Our procedures of data collection and verification are described in this section.

We assume the following types of webpages are credible sources of project information (ranked by credibility): (1) government websites such as the ones for Ministry of Commerce of China and the Embassy of China in the respective countries, (2) official websites of Chinese contractors, (3) official statements and annual reports of publicly-traded Chinese construction companies, (4) official websites of industry organizations such as China Electricity Council and China International Contractors Association, (5) websites specifically covering relevant topics (more discussion below), and (6) media coverage in Chinese state-run press agencies such as Xinhua News Agency and People's Daily Online. Webpages containing photos of contract signing ceremony, construction work on site, commissioning ceremony, and so on have higher credibility and are used whenever possible. Information only seen in corporate news agencies such as Phoenix New Media and SINA Corporation, personal blogs, or online forums is disregarded. The source webpages of this work are primarily in Chinese as English versions of the official websites are often unavailable. Information from English webpages is used to supplement the data collection and verification process.

There are websites that cover specific topics relevant to this work such as "www.bjx.com.cn," which provides a wealth of information regarding the electric power sector in China, and "www.bhi.com.cn," which covers domestic and overseas construction projects that are under development by Chinese contractors. Both of these two websites provide short articles covering individual power plant development projects done by Chinese contractors in overseas countries. Those articles are typically reprints from government websites, companies' official websites, and industry associations' websites. Two other websites of this kind, "wx.havezone.com" and "www.chinagermany.org," only provide names of projects without details but are also used in this work. For a given country, a list of power plant projects can be obtained from those four websites, and while often the information is not comprehensive, it forms a starting point for searching. The steps of the data collection and verification process are as follows:

a. For a given country, create the initial list from the four websites.
b. For each entry in the list, record the name of the power plant project in the master spreadsheet. If the project is already recorded, skip it and go to the next entry in the list.
c. Search the project name using online search engines, namely Google and Baidu, and identify the contractor of the project. If there are multiple contractors for a single project, select the prime contractor instead of the subcontractors.
d. Go to the official website of the contractor and search the website for that project's key information (defined below). If a search engine is not available within the website, the key-word searching is replaced by browsing the website, especially the "company news" section, and finding that project's key information manually. If the contractor does not have an official website, go to step i.
e. Record the key information and reference webpages of that project in the master spreadsheet.
f. In the contractor's website, search the name of the country and browse through the results. If another power plant project in the same country appears, record the key information and reference webpages.
g. In the contractor's website, search the name of the other 14 countries one at a time. Browse the results and record the key information and reference pages whenever a new project is identified.
h. Repeat steps f-g until all projects involving that contractor in the 15 countries are recorded.
i. Go to the search engine results webpage from step c. Browse other credible webpages about the project and record key information and reference pages as needed.
j. In step i, a number of other projects (could be in other countries) are often mentioned in the news reporting of one project. Whenever a new project is seen, repeat steps c-i until no new project remains.
k. Repeat steps b-j until reaching the end of the list of the given country.
l. Go to the next country. Repeat steps a-k until reaching the end of the 15 countries.
m. Search combinations of key words such as "China", "hydropower", "Vietnam", "power plant projects", "electricity cooperation", "contracting", and "contract signing" for different countries and different kinds of power plants in online search engines and read the results extensively. Whenever a new project is seen, repeat steps b-j.
n. Repeatedly confirm information of a recorded project in the master spreadsheet when such information is seen during the search of other projects.

The key information of a power plant development project, which is recorded in the master spreadsheet, includes the location and the kind of power plant, installed capacity, contracting firm, type of contract, date of winning the bid, date of signing the contract, date of starting construction, date of commissioning, and extra notes. Each element of the key information is verified by at least two credible, and independent whenever possible, websites. A project is included in the database if at least one of the four milestone dates identified above is available. We use each project's contract-signing date when plotting the timeseries in Section 4 of this paper. For unavailable contract-signing dates, we calculate them from bid-winning dates or construction-starting dates by assuming contract-signing dates are half a year after the bid-winning dates or one year (for fossil fuel-fired and hydroelectric power plants) or half a year (for wind and solar photovoltaic power plants) prior to the construction-starting dates. Those intervals are estimated from development timelines of similar power plants in the database. In the master spreadsheet, the individual entries are grouped by country and sorted by fuel sources within the country.

Here we discuss the definitions, assumptions, and limitations involved in our data collection and verification process. First, a Chinese contractor is defined in this work as a company that is registered in China, or has its headquarter in China, or is a subsidiary company of a company that is registered in China or has its headquarter in China. Second, a project is included in our dataset if the Chinese contractor plays a significant role in the construction process, including doing the major construction work and/or supplying the key equipment to the project (e.g., turbines and/or boilers for fossil-fuel power plants, generators for hydropower stations, turbines for wind farms, and solar panels and/or solar panel mounting systems for solar photovoltaic power stations). A project is excluded from the dataset if the Chinese company (1) only does small parts of the construction work, which is very rare because being abroad only for a minor amount of work means prohibitive average costs; (2) only performs tasks such as site surveying, engineering consulting, or maintenance; or (3) only provides software and/or electric system support for a power plant. If a consortium formed by Chinese and foreign contractors (e.g., General Electric, Alstom, Siemens, etc.) win the bid as the prime contractor, the project is included in the dataset. Third, power plants of the following kinds account for the majority of overseas power projects built by Chinese contractors and are included in our dataset: coal, gas, oil, nuclear, hydro, solar photovoltaic (PV), wind, biomass, solar thermal, geothermal, municipal solid waste, and cement waste heat recovery.

We make several assumptions when compiling the dataset. First, we assume the information provided by the credible webpages is reliable and up-to-date. In fact, when multiple independent credible websites exist for a single project, they almost always provide consistent information. Second, we assume the projects with missing commissioning dates (or upcoming commissioning dates) will be completed successfully. When evidence occurs that a project would be discontinued, such as the Lamu coal-fired power plant in Kenya that was halted in June 2019 for lack of thorough environmental assessment [41,42], we exclude that project from the dataset to be conservative. Third, power plants operated by regulated utilities and private power companies as well as off-grid power plants dedicated to single manufacturing facilities (i.e., captive power plants) are all included and treated indifferently in our dataset. Fourth, we assume all projects signed by Chinese contractors since October 2013 are associated with the BRI and we refer to them as "BRI projects." BRI is often mentioned in the news coverage of those projects. Our definition of BRI projects is also used by The China Global Investment Tracker but is different from the one used in The China Global Energy Finance database [16,17].

Because Chinese overseas project contracting in the electric power sector is mainly done by fewer than 20 companies [11,23], our company-focused data collection and verification process will provide fairly comprehensive coverage. Nevertheless, there are inherent limitations of this bottom-up approach. First, not all power plant development projects are reported online. A completely comprehensive list cannot be obtained solely from the internet. However, it is reasonable to assume that the large and important projects are always reported on the webpages and are thus included in our dataset. Second, the amount of information posted online may increase with time as the Chinese companies gradually increase their internet use for publicity and marketing. Chinese companies started to have official websites in the 2000s and might only have started to post information on them in recent years. Using the current approach and only taking into account online information may result in an upward bias that more projects are getting done more recently. However, there is no better workaround and the reader should bear this in mind when examining our results.

3.3. Actual power generation and committed CO_2 emissions

Using the collected data on individual power plant development projects in the 15 countries, we estimate the annual power generation and calculate the implied committed CO_2 emissions associated with those power plants. The former requires values of capacity factor while the latter requires values of capacity factor, carbon intensity, and expected lifetime of the power plants. For a power plant,

Annual power generation [MWh] = installed capacity [MW] × capacity factor [–] × 1 [yr], and

Committed CO_2 emissions [kg CO_2] = installed capacity [MW] × capacity factor [–] × carbon intensity [kg CO_2/MWh] × expected lifetime [yr],

where the capacity factor is defined as the ratio of the power plant's actual power generation to its maximum potential generation during a time period, and the carbon intensity is the mass of CO_2 produced per unit of electricity generated for the power plant. The committed CO_2 emissions of a power plant is the lifetime cumulative CO_2 emissions of the power plant. This concept has been used to estimate cumulative future CO_2 emissions from existing and planned fossil fuel-burning infrastructure worldwide using data-driven approaches [43–47] and climate modeling approaches [48]. Different from those studies, this paper specifically focuses on the electric power sector in the 15 representative BRI countries using the collected data. We discuss the assumptions for capacity factor, carbon intensity, and expected lifetime of a power plant below.

The values of capacity factor for each kind of power plants in each of the 15 countries are calculated by finding the actual power generation and maximum potential generation for each country. The capacity factors for fossil-fuel power plants are calculated using two approaches. In the first approach, the actual power generation is taken from the International Energy Agency (IEA) database [49] and the maximum potential generation comes from the plant-level installed capacity data from the GPED database [21]. Because the current version of the GPED database only contains data as of 2010, this approach gives values of capacity factor in 2010, which we assume can be extrapolated to other years. In the second approach, the 2008–12 average values of capacity factor for coal-, gas-, and oil-fired power plants in different regions of the world are taken from the U.S. Energy Information Administration [50]. In this case, countries from the same region (e.g., "Other non-OECD Asia," "Middle East," "Africa," "Other non-OECD Europe and Eurasia," and "Russia") will share the same values. We define the actual values for each country as the average of the resulting values from the two approaches. The values of capacity factor for renewable energy power plants in the 15 countries are calculated using annual power generation and installed capacity data from International Renewable Energy Agency [51] in year 2017.

The values of carbon intensity for fossil-fuel power plants in the 15 countries are also calculated using two approaches. In the first approach, we sum up annual CO_2 emissions of each kind of fossil-fuel power plants in each country in 2010, which come from plant-level CO_2 emissions data in the GPED database, and divide the resulting values by annual power generation of the kind of fossil-fuel power plants in 2010, which comes from the IEA [49]. In this way, we effectively obtain the assumed values of carbon intensity that the authors of the GPED database used to calculate plant-level CO_2 emissions from plant-level installed capacity data, with those values based on carbon contents of the fuels in different regions of the world [52]. In the second approach, the carbon intensity of each kind of fossil-fuel power plants is taken from the GPED database from the countries' corresponding geographic regions. This means countries from the same regions (e.g., "China," "India," "Rest of Asia," "Middle East and Africa," "Russia," and "Europe," as defined in the GPED database) will have the same values. The final values used are the average of the two and, as a check, are compared to the values used in Davis and Socolow [44]. This averaging effectively pushes the country-specific values toward the regional average values. Furthermore, we assume the adoption of new technologies, such as the ultra-supercritical coal-fired power plant that increases combustion efficiency by several percent [53,54], has generally decreased the carbon intensity of fossil-fuel power plants since 2010. Therefore, we multiply the range of carbon intensity values by 0.95–1.0 to form the uncertainty bound. Similar to the previous studies, we assume the carbon intensity of a fossil-fuel power plant stays constant during the plant's lifetime [43,44,47].

Davis and Socolow surveyed 5841 retired power generators from the Platts database and reported that the median lifetime for coal-, gas-, and oil-fired power plants worldwide are 37, 35, and 32 years, respectively, with "no persuasive evidence of systematic differences in relationships among fuel type, region, online year, generating capacity, and retirement year" [44]. Tong et al. reported that the global average lifetimes of retired coal-, gas-, and oil-fired power generators are 35.9, 37.1, and 33.9 years, respectively, combining data from the GPED database, the China coal-fired Power plant Emissions Database [55], and the Platts database [47]. Both Davis and Socolow and Tong et al. used a single reference lifetime of 40 years for all fossil-fuel power generators in their analyses with 30–50 years as the uncertainty range and performed sensitivity analysis using lifetimes of 20–60 years [44,47]. Because we focus on specific regions, we use the more specific reference lifetimes of 37, 35, and 32 years for coal-, gas-, and oil-fired power plants, respectively, from Davis and Socolow [44]. We also use 0.8–1.2 × reference lifetimes to construct the uncertainty bounds, consistent with the earlier studies [44,47].

The final values of capacity factor, carbon intensity, and expected lifetime used in this paper as well as the corresponding values from literature are summarized in Tables S3–S5 in the SI.

4. Results and discussion

We examine and analyze our dataset in Sections 4.1 and 4.2. In Section 4.3, we present and discuss the carbon emissions implications of the power plant projects using committed CO_2 emissions. Finally, we discuss policy implications in Section 4.4.

4.1. Aggregate analysis

In this section, we look at the power plant construction projects involving Chinese contractors in the 15 representative BRI countries between January 2005 and June 2019, and assess how the introduction of BRI may have impacted those activities. Fig. 2A plots the total added generation capacity in the 15 countries as a function of time, with time represented by the contract-signing dates of individual projects. Fig. 2B plots the total number of power plant projects in the 15 countries using the same horizontal axis. Only six kinds of power generation capacity are shown in Fig. 2 because the others either involve too small capacity or too few projects. The vertical red line indicates the last day of September in 2013, which we take as the starting date for the Belt and Road Initiative.

Several observations can be made from Fig. 2A. First, coal has a larger rate of increase than other kinds of generating capacity over the whole period, while gas and hydro form the second-tier members. Oil, solar PV, and wind are the third-tier members and have similar cumulative added capacity as of 2019. Second, the shapes of the curves indicate that the increase in oil is dominated by few large projects while solar PV and wind involve a larger number of smaller projects compared to oil. Third, there appears to be a one-time increase in slope for coal and gas curves in late 2015. The two curves are roughly linear before and after the change of slope. The time of the slope change might reasonably be seen as the start of the BRI, with an appropriate time lag for project initiation. Fourth, the increase of hydro capacity is approximately linear throughout the entire time period. Finally, solar PV and wind capacities both increased from zero in early 2013. Solar PV capacity surpassed wind in early 2018, but both capacities remain small.

Fig. 2B provides additional insights into the activities. First, the hydro curve is now away from the gas curve and closer to the coal curve, as compared to Fig. 2A. This means the hydro power plants on average have smaller capacity than coal and gas power plants. Second, the one-time increase of slope for the coal and gas curves in late 2015 seen in Fig. 2A can also be seen in Fig. 2B, although less evidently. The curve for hydro appears to have a one-time decrease in slope also around 2015, although the change is small. Third, the increase of solar activities since early 2017 is shown more dramatically in Fig. 2B. As of June 2019, Chinese contractors have been involved in similar numbers of hydro and solar PV projects and similar numbers of gas and wind projects in the 15 countries. The number of oil-fired power plant projects is small, confirming the observation from Fig. 2A.

In summary, our data indicate that both total installed generation capacity and total number of signed projects for coal- and gas-fired power plants exhibit higher rates of increase after BRI was introduced. Hydroelectricity and wind power generation capacity have increased steadily through time, while the number of signed projects exhibit lower and high rates of increase, respectively, after the creation of BRI. The number of solar PV projects has experienced dramatic increase since 2017, although the cumulative PV generation capacity is still low.

4.2. Country by country analysis

To complement the aggregate analysis, in this section we explore the increase of power generation capacity in each of the 15 countries individually through time. We also summarize the amounts and kinds of power generation capacity added by the projects that were signed after the initiation of BRI, and assess how those post-BRI additions influence the power generation mix in the 15 countries.

As seen in Fig. 3, where the 15 countries are grouped according to their regions, Southeast Asian countries have the earliest relations with Chinese contractors and the largest number of projects among all regions. This makes sense because the populous Southeast Asian countries have early and strong demand for power development and because Southeast Asian countries are geographically and culturally close to China and were naturally targeted by Chinese firms when they started doing business abroad. Fig. 3 reveals that the early increases of coal and hydro capacities in Fig. 2B are primarily caused by projects in Vietnam and Indonesia. Vietnam has a large number of small hydro plants [56], defined as 30-megawatt (MW) or less, and that confirms the early observation from Fig. 2 that hydro plants have smaller capacity compared

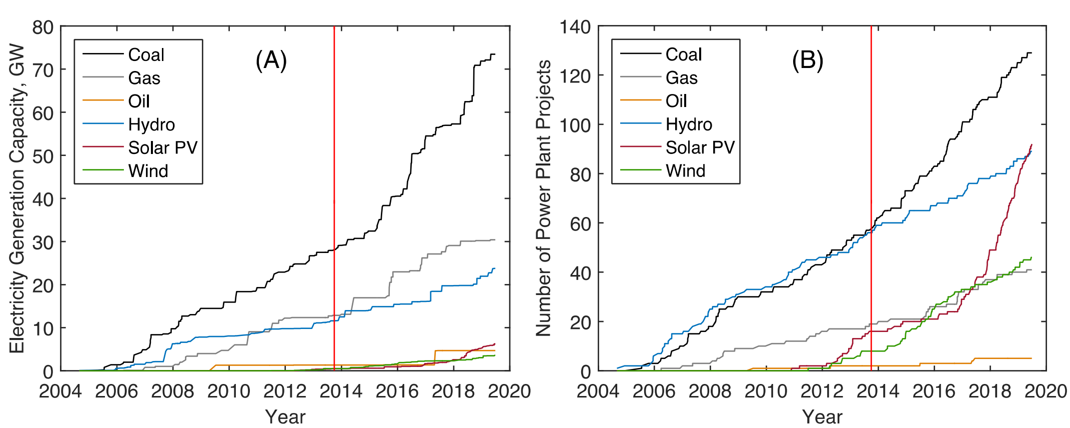

Fig. 2. (A) Cumulative power generation capacity and (B) total number of power plant projects involving Chinese contractors in the 15 representative BRI countries. The horizontal axis indicates contract-signing dates. The vertical red line indicates the last day of September in 2013, which we take as the starting date for the BRI.

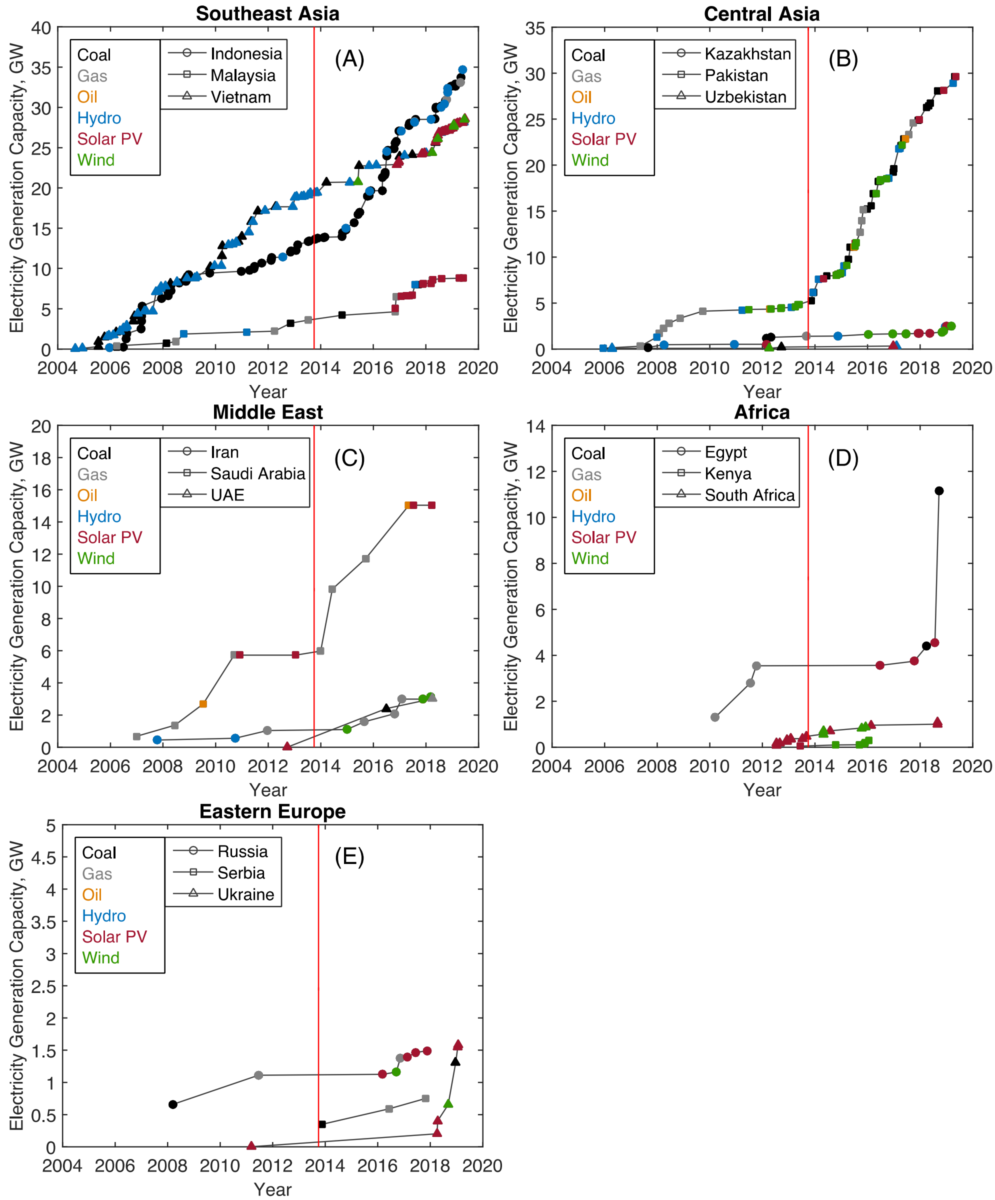

Fig. 3. Cumulative power generation capacity added by projects involving Chinese contractors in countries from (A) Southeast Asia, (B) Central Asia, (C) the Middle East, (D) Africa, and (E) Eastern Europe. The color of markers shows the kind of power plant projects. The horizontal axis indicates contract-signing dates. The vertical red line indicates the last day of September in 2013, which we take as the starting date for the BRI. The scale on the vertical axis is different in each of the subplots.

to coal and gas plants. The curve for Indonesia becomes steeper after the introduction of BRI, and the coal-fired power plant projects there contribute to the continued growth of coal activities as shown in Fig. 2.

There is a noticeable increase of solar PV and wind projects in Vietnam since 2017, likely due to the revised National Power Development Master Plan of Vietnam, which was approved in March 2016, that planned to increase solar generation capacity in Vietnam from a negligible level in 2016 to 850 MW in 2020, 4 gigawatts (GW) in 2025, and 12 GW in 2030, and a similar increase path for wind power [57,58]. In the case of Malaysia, the first Large Scale Solar PV Tender that took place in 2016 as well as the series of renewable energy-encouraging policy and programs introduced thereafter [59–61] likely contribute to the increased number of solar PV projects in Malaysia since 2017.

Central Asian countries also have relatively early business relations with Chinese contractors. In Pakistan, the power development cooperation commenced just after BRI was introduced. The total added capacity and the number and variety of projects all increased significantly compared to the pre-BRI era. These increases are associated with the China-Pakistan Economic Corridor (CPEC), a flagship BRI bilateral agreement involving infrastructure investment and development in Pakistan to address its energy shortage and boost its economy [62]. The first large power plant developed under the CPEC, the 1320-MW Sahiwal coal-fired power plant, started operation in July 2017. The projects in the other two Central Asian countries, Kazakhstan and Uzbekistan, are all renewable ones after the introduction of BRI, although their combined installed capacity is much smaller than Pakistan.

The projects in the Middle East primarily focus on gas-fired generating capacity, consistent with the dominant power generation mix in the region. There are noticeable increases in added capacity in all three Middle Eastern countries following the creation of BRI. The power cooperation in Africa started relatively late. All projects in Kenya and South Africa are renewables, and the conspicuous increase of generation capacity in Egypt in 2018 is caused by the 6000-MW Hamrawein

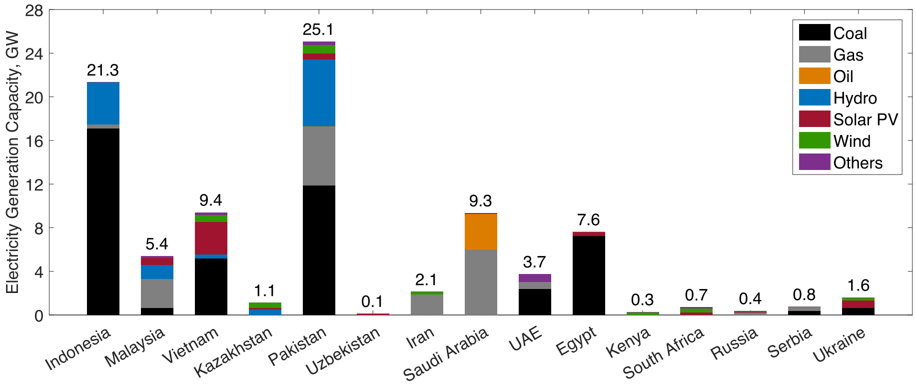

Fig. 4. Electricity generation capacity added by BRI projects after their completion. BRI projects are defined as the power plant development projects involving Chinese contractors in the 15 BRI countries from October 2013 to June 2019. "Others" include biomass, solar thermal, geothermal, municipal solid waste, and cement waste heat recovery generating capacity. The significant amount of "Others" in UAE is a 700-MW concentrated solar thermal power plant. The unit in this figure is power generation rate, gigawatt. Specific values are presented in Table S6 of the SI.

ultra-supercritical coal-fired power plant project. There are relatively small numbers of projects with overall small added capacity in Eastern Europe compared to other regions. Most of them are gas and solar PV projects.

The results and analyses so far indicate that, after the initiation of BRI in September-October 2013, Chinese engineering contracting companies were involved in more projects in Southeast and Central Asian countries, where they have had early business relations, and started new business in the Middle Eastern, African and European countries that are geographically distant from China. The kinds of projects done in the 15 countries appear to be consistent with the regional generation mix (shown in Table S1 of the SI) and with policy and situations in individual countries. The share of total power generation capacity involving Chinese contractors among the five geographic regions is consistent with the result shown in Hannam et al. [14].

Next, we focus on the amounts and kinds of power generation capacity added by the BRI projects, which are defined as projects whose contract-signing dates are later than October 2013, and assess how those additions would impact the power generation mix in the 15 countries.

Fig. 4 indicates that BRI projects are adding large electricity generation capacity to Pakistan, Indonesia, Vietnam, Saudi Arabia, and Egypt. This is consistent with the fact that four of these five countries (except Saudi Arabia) have announced plans to dramatically increase (often double) their installed power generation capacity in the next decade [63–69]. The top 3 in the absolute amount of fossil fuel capacity additions are Indonesia (17 GW), Pakistan (17 GW), and Saudi Arabia (9 GW). In terms of percentage of fossil fuel capacity additions, the top 3 are Serbia (100%), Saudi Arabia (99%), and Egypt (95%). The top 3 in the absolute amount of renewable capacity additions are Pakistan (8 GW), Vietnam (4 GW), and Indonesia (4 GW), while those with large percentage additions of renewables are Kazakhstan (100%), Uzbekistan (100%), Kenya (100%), South Africa (100%), Ukraine (59%), and Vietnam (45%). Overall, for the period from October 2013 to June 2019, 51.1% of total added generation capacity goes to coal, 19.7% goes to natural gas, 3.7% goes to oil, 13.7% goes to hydroelectricity, 6.5% goes to solar PV, 3.5% goes to wind, and 1.8% goes to others including biomass, solar thermal, geothermal, municipal solid waste, and cement waste heat recovery.

We further investigate how the generation capacity added by the BRI projects changes the power generation mix in the 15 countries. In Fig. 5, each country has a pair of bars in the bar chart, with the left bar in each pair showing that country's electricity generation mix in 2013 (i.e., before signing BRI projects) and the right bar showing the expected generation mix after BRI projects are completed in that country. Note that the right bars for different countries do not necessarily indicate the same point in time because the BRI projects in different countries could finish in different years. Also, because non-Chinese companies are building power plants in those 15 countries at the same time, the right bars would not represent the total overall power generation mix in any of those 15 countries at any time. Comparison of the left and right bars of a country only reflects the changes caused by the BRI projects.

Fig. 5 indicates that power generation in Pakistan will be doubled, and the percentage of coal will increase significantly. This is consistent with the Pakistan government's plan to diversify the country's power generation mix and increase domestic hydrocarbon production [70], which could alleviate pressure on its foreign exchange reserves (for

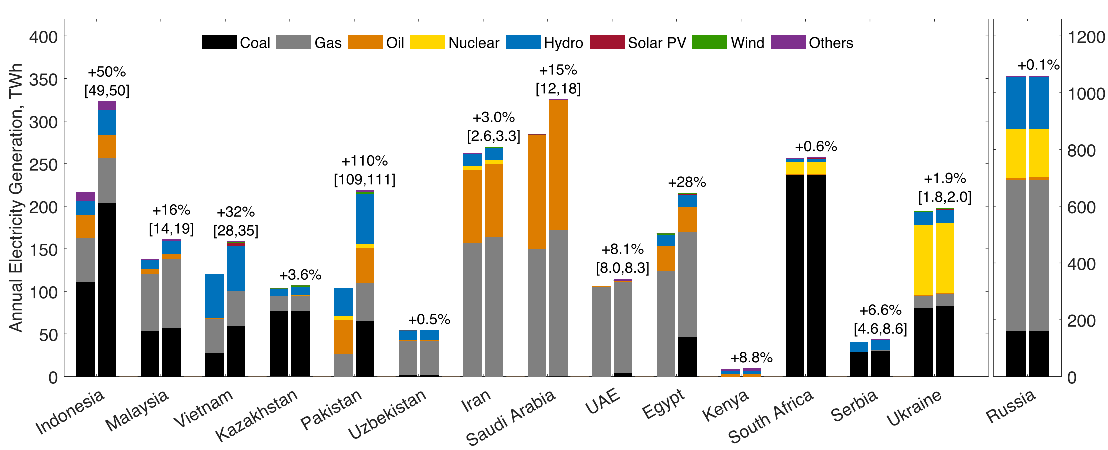

Fig. 5. Power generation mix in the 15 BRI countries before construction and after completion of BRI projects. "Others" include biomass, solar thermal, geothermal, municipal solid waste, and cement waste heat recovery generating capacity. The number shows the percentage increase in total annual power generation from 2013 to the time when BRI projects are completed in that country. Numbers in square brackets are the uncertainty ranges resulting from using country-specific values of capacity factor (as illustrated in Section 3.3). The unit in this figure is terawatt-hour.

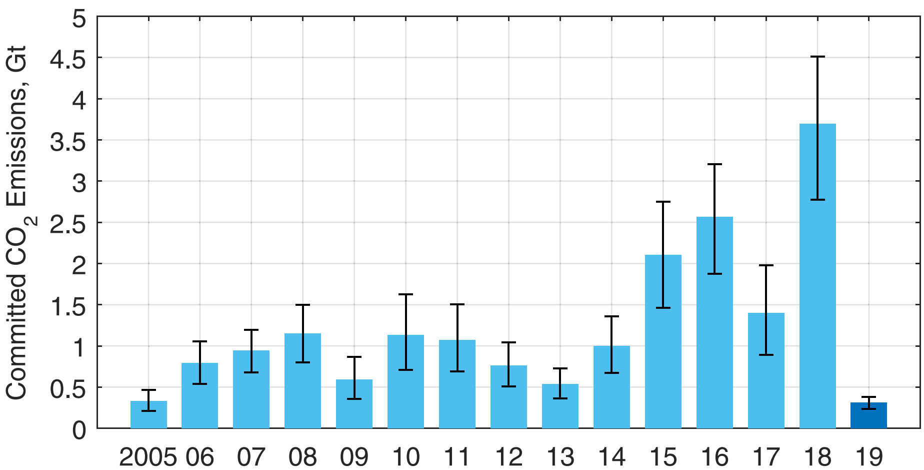

Fig. 6. Committed CO_2 emissions from the power plant projects signed by Chinese contractors in the 15 countries in each year from January 2005 to June 2019. Calculation procedures are described in Section 3.3. The error bars result from uncertainties in country-specific values of capacity factor, carbon intensity, and expected lifetime of the power plants. The dark blue column of 2019 only contains projects signed in the first six months of 2019.

purchasing large amount of oil and gas from the Middle East), improve energy security, and generally boost its domestic economy. In addition to Pakistan, the total annual power generation will increase more than 15% in Indonesia, Malaysia, Vietnam, Saudi Arabia, and Egypt, and the percentage of power generation from coal would increase significantly in Indonesia, Vietnam, and Egypt. Increases in power generation from renewables are noticeable in Vietnam, Pakistan, and Ukraine, but only cause little change to the overall power generation mix. The renewables are less detectable in Fig. 5 comparing to Fig. 4 due to the small values of capacity factor associated with solar PV and wind in many of those countries.

4.3. Carbon emissions implications

We now move away from examining the dataset itself and start analyzing the carbon emissions implications of the power plant projects. We start by calculating the committed CO_2 emissions associated with the projects signed by Chinese contractors in the 15 countries in each year from January 2005 to June 2019.

Fig. 6 shows that the committed CO_2 emissions of signed projects gradually increases from the 2005 level, has a noticeable drop in 2009, and gradually decreases from 2010 to 2013 after recovering from the 2009 level. The committed CO_2 emissions start to grow again in 2014, with peak value in 2018. The committed emissions are likely to drop in 2019, based on the small number from the first six months of 2019. On average, the committed CO_2 emissions for signed power plant projects in years after 2013 are clearly higher than the ones before 2013. The relatively high level after 2013 is mainly caused by the large number of fossil-fuel power plants in Indonesia and Pakistan and a few large fossil-fuel power plants in Saudi Arabia and Egypt, as shown by Fig. 3.

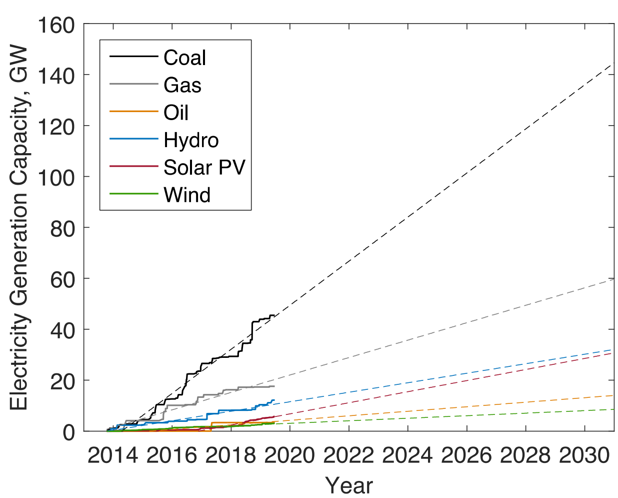

Fig. 7. Linear extrapolation of total power generation capacity added by BRI projects in the 15 representative BRI countries to the end of 2030.

The overall trend in Fig. 6 makes sense. Fossil fuel power plants are typically capital-intensive and require strong financial capability from the investor. The drop in 2009 was likely caused by a decrease in the number of fossil fuel projects in the BRI regions in the aftermath of the global financial crisis of 2008. In general, the trend in Fig. 6 is broadly consistent with the trend of annual value of newly signed overseas power construction contracts by Chinese contractors from 2006 to 2017 [23] and the trend of annual amount of financing by Chinese policy banks in overseas power generation sector from 2000 to 2018 [16].

In the rest of this section, we look at possible future development of the electric power sector in the BRI regions. We first extrapolate the cumulative BRI-added generation capacity curve to the end of 2030 and calculate the associated committed CO_2 emissions. We then upscale that number from the 15 countries to all BRI countries to estimate the total projected committed CO_2 emissions from BRI-associated power development by the end of 2030. Finally, we bring the results into the context of total globally allowable CO_2 emissions to achieve the “well below 2 °C and even further to 1.5 °C in this century” climate goal stated in the United Nation Paris Agreement [71]. We also discuss different scenarios of the power development paths and estimate the emissions implications of each.

We estimate the total added electricity generation capacity in the 15 representative BRI countries by the end of 2030 using linear extrapolation of current data. The results are plotted in Fig. 7. For all methods of power generation capacity except solar PV, the linear extrapolation is based on data from October 2013 to June 2019. For solar PV capacity, we base the linear extrapolation on data from January 2017 to June 2019, assuming the increase of solar PV generation capacity since early 2017 is sustainable and will continue in the next decade. Overall, the total added capacity is projected to be 290 GW from October 2013 to the end of 2030. Assuming the partitioning of each kind of generation capacity in each of the 15 countries stays the same as in June 2019, this projection means 1.5 (range 1.4–1.7) TWh of electricity is added to the 15 countries during the period from October 2013 to the end of 2030 and the increase rate is 63 (range 57–69) kilowatt-hours (KWh) per capita per year. This number is higher than, but on the same order of magnitude as, the average annual increase of electricity consumption in the world from 1971 to 2014, which is 45 KWh per capita per year [72]. Note that if the capacity factors of solar PV and wind generation in the 15 countries increase in the next decade, ceteris paribus, the 63 KWh per capita per year would be an underestimate.

The breakdown of the 290 GW is the following: coal: 145 GW

(50.0%); gas: 60 GW (20.6%); oil: 14 GW (4.8%); hydroelectricity: 32 GW (11.1%); solar PV: 31 GW (10.6%); and wind: 8 GW (2.9%). Using the average values of capacity factor and carbon intensity for coal, gas, and oil power plants weighted by the partitioning of each generation capacity in each of the 15 countries in June 2019 (see SI Table S7), we estimate the fossil fuel-fired generation capacity added to the 15 countries by the end of 2030 would produce 37 (range 26–48) gigatonnes (Gt) of committed CO_2 emissions.

Next, we upscale the committed CO_2 emissions from the 15 countries by extrapolating from the 15 representative countries to all of the BRI countries. To do this, we use the latest official annual report on Chinese international project contracting [23], which states that the total value of newly signed project-contracting contracts by Chinese firms in these 15 countries was 96.14 billion USD in 2017 and the value for (unspecified) "countries along the Belt and Road regions" was 144.32 billion USD in 2017. The ratio of the two values is 1.50. We use the value of 1.5 to scale up the emissions from the 15 representative countries, which means the total committed carbon emissions from all BRI-related power development projects from October 2013 to the end of 2030 would be 56 (range 40–72) Gt CO_2. We assume this ratio, which accounts for project contracting in multiple sectors, can be used for only the electric power sector, and that this ratio of monetary values can be used to upscale power generation capacity.

The Intergovernmental Panel on Climate Change (IPCC) and many other studies on climate modeling have reported that the relationship between cumulative emissions of CO_2 and the increase of global mean surface temperature relative to the pre-industrial levels is almost linear [73,74]. This leads to the concept of "carbon budget," which is a simplified way to measure the amount of additional CO_2 emissions that can enter the atmosphere if the world wants global warming to stay below a certain temperature limit. Estimates of this budget, however, vary significantly due to the complexity of Earth's climate system, the sensitivity to the modeling approach, and the ambiguity of terms such as "surface temperature" and "pre-industrial" period. In this paper, we use the estimates from the recent (October 2018) IPCC *Special Report on Global Warming of 1.5 °C*, which assessed a wide range of estimates and suggested a remaining carbon budget of about 420 Gt CO_2 from the start of 2018 for a 67% chance of limiting warming to 1.5 °C and of about 580 Gt CO_2 for a 50% chance [74]. For strict definition of the terms and uncertainties involved in these numbers and more general discussion of the carbon budget, the reader is referred to the IPCC report and Rogelj et al., respectively [74,75].

Putting the 56 (range 40–72) Gt committed CO_2 emissions to the 420–580 Gt CO_2 context reveals that the BRI-associated power development from the initiation of BRI to the end of 2030 would take 7–17% of the remaining carbon budget. On one hand, those are not overwhelmingly large numbers, given that 42% of world's population lives in the BRI regions and many of the BRI countries are currently at low levels of economic development with relatively high growth rate. On the other hand, limiting warming to 1.5 °C implies reaching net-zero CO_2 emissions globally by the middle of this century [74]. Given the current global anthropogenic CO_2 emission rates of about 42 $\pm$ 3 Gt CO_2 per year (including fossil fuel and land-use change emissions) [74,76], enormous reductions in annual net carbon emissions will need to be made. An additional 56 (range 40–72) Gt committed CO_2 emissions from BRI-related electric power development would make it notably more difficult to achieve the emission reduction target.

The results shown in this section are based on extrapolations of the current trends over the next decade and are thus uncertain. Fig. 3 indicates that the primary drivers of the growth of fossil fuel capacity from October 2013 to June 2019 are Indonesia and Pakistan. If the development of power sectors in other BRI countries is not as fossil fuel-focused as in Indonesia or Pakistan from now to 2030, the 56 (range 40–72) Gt and 7–17% numbers would overestimate the carbon emissions associated with the BRI. In fact, BRI countries such as Vietnam, Cambodia, and Saudi Arabia have recently set plans to expand renewables in their power generation mix [77–80]. Moreover, fewer fossil-fuel construction projects were signed through the first half of 2019 comparing to previous years, as shown by Fig. 6. This may indicate an early flattening of the growth curves for fossil fuel-based power generation, leading to lower projected emissions. If the increase of fossil fuel generation capacity flattens by the end of 2025 and the space is filled by renewables (so that total installed generation capacity stays the same in 2030), the committed carbon emissions of BRI-related power development would be 39 (range 28–50) Gt CO_2 and would take 5–12% of the remaining carbon budget. If the increase of fossil fuel generation capacity flattens by the end of 2020, then the numbers would be 23 (range 16–29) Gt CO_2 and 3–7% of the remaining carbon budget. Of course, if pro-fossil-fuel policies and associated investments are expanded over the next decade, then the committed emissions would be higher than the base case of 56 Gt CO_2.

We note three things to conclude this section. First, the high growth in solar PV capacity starting in early 2017 is largely caused by the increase in the number of solar PV projects in Vietnam and Malaysia, as shown in Fig. 3. This could mean that the linear extrapolation of solar PV power generation capacity is too optimistic – when the demand in those two countries is met, the growth rate would decrease if no other country develops large amounts of solar PV. At the same time, it is possible that the success of solar PV in Vietnam and Malaysia could spread to other countries in Southeast Asia, which could sustain or even boost the growth of solar PV in BRI. Second, wind power is projected to only make up 2.9% of installed power capacity in 2030 from the current linear extrapolation. However, wind potential is large in Central Asia and Northern Africa [81], and there might be more wind power projects in the future in the BRI countries. Finally, we stress that the added power capacity numbers and associated emissions are only those we identify with BRI projects, and do not represent the total overall power development in these countries.

4.4. Policy implications

In addition to calculation of committed CO_2 emissions in the context of remaining carbon budget, we also compute the "avoided CO_2 emissions" resulting from the expansion of solar PV and wind generation capacity. Comparison of this number to the committed emissions from fossil fuels can provide insights into how "green" the BRI-related power development is. The avoided CO_2 emissions are calculated in the same way as the committed CO_2 emissions but using "displaced fossil fuel capacity," which is obtained by first summing up the total added solar PV and wind capacity during a period of time and then allocating the sum to coal, gas, and oil using the partitioning of fossil-fuel generation capacity at the end of the period. The "greenness ratio" for the power development during the period of time is then defined as the ratio of avoided CO_2 emissions to committed CO_2 emissions, both produced by the increase of installed generation capacity during the period. For the base case of 56 Gt committed CO_2 emissions at the end of 2030, the avoided emissions are 10 (range 7–13) Gt CO_2, and the greenness ratio is 0.2. The resulting values for each of the three projection scenarios to 2030 are summarized in Table 1. Larger values of the greenness ratio correspond to larger contributions from renewables.

The "New Policies" scenario in IEA's World Energy Outlook 2018 [8], which takes into account energy plans and targets recently announced by governments around the world including the Nationally Determined Contributions of the Paris Agreement, suggests that the incremental installed power generation capacity in Africa, Middle East, Eurasia, and Southeast Asia (broadly the BRI regions) between 2016 and 2030 would have a greenness ratio of 1.5. The incremental capacity in that scenario has a larger percentage of gas and smaller percentage of coal, compared to the mix of BRI-related 290 GW capacity in the 15 countries. The "Current Policies" scenario, which only considers worldwide energy policies that have passed the legislation as of mid-2018, and the "Sustainable Development" scenario, whose energy

Table 1
Summary of the values associated with the three projection scenarios to 2030 in Section 4.3.

Scenario	15 Representative BRI countries										All BRI countries			
	Total added capacity from Oct. 2013 to Dec. 2030 (GW)	Coal (GW)	Gas (GW)	Oil (GW)	Hydro (GW)	Solar PV (GW)	Wind (GW)	Total added power generation (TWh)	Fossil fuel commited CO_2 emissions (Gt)	Avoided commited CO_2 emissions (Gt)	Fossil fuel committed CO_2 emissions (Gt)	% of remaining 1.5 °C carbon budget	Avoided committed CO_2 emissions (Gt)	Greenness ratio
#1 (Base case)	290	145 (50%)	60 (20%)	14 (5%)	32 (11%)	31 (11%)	9 (3%)	1.5 (1.4–1.7)	37 (26–48)	7 (5–9)	56 (40–72)	7%-17%	10 (7–13)	0.2
#2 (Flattens in 2025)	290	101 (35%)	43 (15%)	10 (3%)	32 (11%)	80 (28%)	24 (8%)	1.1 (1.0–1.2)	26 (19–34)	18 (13–23)	39 (28–50)	5%-12%	27 (19–34)	0.7
#3 (Flattens in 2020)	290	58 (20%)	25 (9%)	5 (2%)	32 (11%)	121 (42%)	48 (16%)	0.6 (0.6–0.7)	15 (11–19)	29 (20–37)	23 (16–29)	3%-7%	43 (30–55)	1.9

objectives are derived from Sustainable Development Goals of the United Nation, from the IEA Outlook have greenness ratios of 0.5 and 1.8, respectively. The BRI-related power development as reported in this paper needs to have a much larger greenness ratio to follow the IEA's mitigation scenarios (more analyses is provided in Figs. S1 and S2 in the SI). The greater greenness ratio can be achieved by earlier flattening of fossil-fuel capacity curves and/or building additional solar PV and wind capacity.

The emphasis on clean and sustainable development stated in official BRI documents [1,35–37] as well as the newly published *Green Investment Principles for the Belt and Road*, a voluntary code of practice aiming to incorporate low-carbon development into the BRI [82], should encourage Chinese enterprises to place more weight on climate considerations when making investment decisions and taking on power plant construction projects. The greenness ratio defined in this section could be an effective way to measure the greenness of BRI in the electric power sector. A more ambitious action could involve the Chinese government considering an extension of its national carbon market, which was launched in late 2017 in its pilot form [83,84], to a regional one that includes the BRI countries. China could also promote the use of carbon mitigation technologies such as carbon capture and storage [85,86] in the fossil-fuel power projects associated with BRI.

5. Conclusions

In this study, we collect and analyze publicly available information for 458 power plant development projects in 15 representative countries along the Belt and Road regions since 2005, in which Chinese engineering contracting companies have major involvement. The focus on contracting companies in this work not only supplements previous studies, which examine Chinese financial investment in power plant projects in the BRI countries, but also in itself provides a more comprehensive picture of Chinese companies' involvement in the development of the electric power sector of the BRI regions, since a large portion of the projects with Chinese investment also hire Chinese engineering contractors.

For the 15 representative BRI countries examined in this study, both total installed generation capacity and total number of signed projects for coal- and gas-fired power plants show higher rates of increase since late 2015. Additional hydroelectricity and wind power generation capacity has increased steadily through time, although the numbers of signed projects for each of them have increased at a lower and a greater rate, respectively, since late 2015. The number of solar PV projects has experienced dramatic increase since early 2017, although the cumulative PV generation capacity is still low compared to fossil fuel and hydroelectricity capacities. Upon completion, the BRI-related increase in power generation capacity will double Pakistan's annual power generation compared to its 2013 level and create more than 20% increases in Indonesia, Vietnam, and Egypt.

Since the beginning of BRI in late 2013, 75% of new generation capacity developed in these 15 countries with Chinese contractors has gone to fossil fuel-burning power plants, 14% has gone to hydroelectricity, and the remaining 11% has gone to other renewables including solar PV and wind. Although the kinds of projects appear to be consistent with country-specific situations and typical electricity-generation mixes in different world regions, the dominance of fossil fuel in the new generation capacity has important carbon emissions implications. Linear extrapolation of current trends indicates that the total BRI-associated power development in the 15 countries could generate 37 (range 26–48) Gt of committed CO_2 emissions by the end of 2030. Upscaling this result to all BRI countries gives an estimate of approximately 56 (range 40–72) Gt committed CO_2 emissions by 2030, corresponding to 7–17% of the remaining carbon budget for the 1.5-degree climate goal. If the projected growth of fossil fuel power generation slows down by the end of 2025 and 2020, the committed emissions of BRI-associated power development would reduce to 39 (range 28–50)

Gt CO_2 and 23 (range 16–29) Gt CO_2, respectively. However, if pro-fossil-fuel policies are expanded over the next decade, the committed emissions would be higher than the base case.

Results in this paper highlight the importance and urgency of reducing fossil fuel dominance and expanding renewable energy in BRI-associated electric power development. BRI is a unique platform for all participating countries to collaborate on energy policymaking so that the greenness ratio of the aggregate power sector development can increase to the level comparable to IEA's mitigation scenarios. The emphasis on clean and sustainable development stated in the founding documents of BRI should guide investment decisions and the associated construction of power infrastructure. More ambitious actions from BRI to reduce carbon emissions, such as creating a regional emissions trading scheme and promoting the use of carbon mitigation technologies in its fossil-fuel power projects, could be enormously beneficial. If the BRI prioritizes green development, the world will benefit in many ways, while China could become the world leader in climate-friendly technologies and policies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.114784.

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