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Digital Object Identifier (DOI):
10.1038/s41893-021-00704-8

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Abstract

China has built the world's largest power transmission infrastructure by consuming massive volumes of greenhouse gas (GHG)-intensive products such as steel. A quantitative analysis of the carbon implications of expanding the transmission infrastructure would shed light on the trade-offs among three connected dimensions of sustainable development, namely climate change mitigation, energy access and infrastructure development. By collecting a high-resolution inventory, we developed an assessment framework of, and analysed, the GHG emissions caused by China's power transmission infrastructure construction during 1990–2017. We show that cumulative embodied GHG emissions have dramatically increased by more than 7.3 times those in 1990, reaching 0.89 Gt CO_2 eq. in 2017. Over the same period, the gaps between the well-developed eastern and less-developed western regions in China have gradually narrowed. Voltage class, transmission line length and terrain were important factors that influenced embodied GHG emissions. We discuss measures for the mitigation of GHG emissions from power transmission development that can inform global low-carbon infrastructure transitions.

In recent decades, China's power transmission infrastructure has experienced rapid development[1,2], mainly driven by the enormous electricity consumption[3] that has occurred against a backdrop of the long distances between power generation and load centres[4]. To guarantee a reliable power supply, vast amounts of money and other resources have been devoted to the construction of China's power transmission infrastructure. In 2017 alone, 78.7 billion USD was spent on power transmission construction[5]. Given this unprecedented level of expenditure, China now possesses the world's largest power transmission infrastructure[6]. Its transmission lines with voltage classes over 220 kV reached 6.87E+05 km in 2017, approximately twice that of Europe[7]. Notably, China's power transmission infrastructure will be expanded in the foreseeable future motivated by the demand to meet fast-growing renewable power[8,9] and ambitious strategies such as global energy interconnection[10].

The construction of infrastructure has profoundly harmful environmental impacts[11-13], and power transmission infrastructure is no exception. China's great achievement in power transmission infrastructure has been gained at the cost of consuming substantial amounts of greenhouse gas (GHG)-intensive inputs such as steel, which produce a large amount of GHG emissions via their supply chains[14,15]. Nevertheless, only a handful of studies have made initial attempts to analyse the GHG emissions resulting from regional power transmission infrastructure in several developed countries[16,17]. These studies have suggested that power transmission systems have great impacts on global climate change; however, these studies have been limited due to a lack of a comprehensive and systematic investigation. First, the focus of the previous studies has been confined to specific components of the whole power transmission infrastructure such as overhead lines, underground cables[18,19], transformers, and substation equipment[20]. Second, the consideration of important inputs such as communication and auxiliary power equipment has been missing. Finally, the factors that influence the GHG emissions induced by power transmission infrastructure, specifically, voltage class and terrain conditions, have not been identified.

In this study, we have developed an assessment framework that, for the first time, provides a holistic picture of embodied GHG emissions from China's large-scale power transmission construction during the period from 1990 to 2017. We began by compiling a detailed inventory of the national power transmission system. The dataset includes information on more than 10,000 types of input for 191 typical power transmission infrastructure projects comprising 145 types of alternating current (AC) overhead transmission line project, 37 typical AC substation projects, 8 typical direct current (DC) overhead transmission line projects and 1 typical DC convertor station project. The detailed input inventory of all the projects investigated by this study can be found on our dataset websites[21]. We then calculated the annual addition and the cumulative GHG emissions (defined as the sum of the annual addition emissions) from China's national power transmission infrastructure construction using a hybrid method as a combination of process analysis and input-output analysis[22,23]. We also assessed the impact of some important factors, such as transmission line length and nameplate capacity, on the embodied GHG emissions (nameplate capacity is also known as nominal capacity, rated capacity or installed capacity, referring to the conventional value of apparent power under principal tapping). We analysed the emission uncertainty using Monte Carlo simulation (see the Methods section) by considering the uncertainties from GHG emission intensities, input inventories, and the depreciation rate of the power transmission infrastructure. We also make a comparison with the existing research using life cycle assessment (LCA) (see the Supplementary Information - Comparison with previous research) to verify the robustness of this assessment framework. Additionally, we estimated China's provincial GHG emissions induced by power loss (see the Supplementary Information - The GHG emissions of power loss), which has been recognized as the major contributor to the GHG emissions from power transmission[24]. By comparing with GHG emissions induced by power loss, we can have a more comprehensive understanding of the scale of embodied GHG emissions from power transmission infrastructure.

Our results show that the cumulative GHG emissions caused by China's power transmission infrastructure construction drastically increased from 1990 to 2017. Although a very large gap existed between the embodied emissions in the eastern and western regions, the gap gradually narrowed as the distribution of power transmission infrastructure became more balanced across China. The key influential factors for the embodied emissions were also identified. Our study can provide insights into GHG emission mitigation in power transmission infrastructure construction in China and other developing countries, and the assessment framework in this study can also be used to assess other environmental impacts such as those of transportation, energy and telecommunications infrastructure.

Rapidly growing cumulative embodied GHG emissions

In 1990, the cumulative embodied GHG emissions induced by China's power transmission system were 0.12 Gt. In 2017, this figure had dramatically increased by more than 7.3 times and reached 0.89 Gt (Fig. 1). Among these emissions, substation and transmission line infrastructure account for 0.46 Gt and 0.43 Gt, respectively. These growing cumulative emissions are mainly attributable to China's vast investment in the national power transmission infrastructure[25]. The majority of the investment has been used to purchase GHG-intensive products such as electrical equipment to build power transmission infrastructure[26]. Notably, approximately 90% of the total GHG emissions are from four economic sectors (Manufacture of basic iron and steel and of ferro-alloys and first products thereof; Manufacture of fabricated metal products, except machinery and equipment; Manufacture of electrical machinery and apparatus, nec; and Construction). By contrast, China's decreasing embodied GHG emission intensities (Supplementary Figure 1) contributed to a remarkable amount of emission reduction from infrastructure construction. In particular, the GHG emission intensities of the metallurgy, electrical equipment, and construction sectors, as the major suppliers of power transmission systems, decreased by 76%, 81% and 76% from 1990 to 2017, respectively, due to China's progress in energy efficiency improvements and energy structure adjustments. Meanwhile, the uncertainties of the annual embodied GHG emissions caused by power infrastructure were approximately -14% and +19% at the 95% level of confidence during the period from 1995 to 2015 (detailed results are presented in Supplementary Table 1).

The structure of GHG emissions embodied in transmission projects with different voltages shows remarkable changes (Fig. 1). In 1990, 220 kV overwhelmingly dominated the cumulative GHG emissions while 330 kV and 500 kV accounted for only minor shares. In the early 1990s, coal transportation played a central role in inter-provincial energy transmission, and 220 kV systems could satisfy the power transmission needs that occurred mainly within each provincial region[27]. However, the 220 kV systems gradually became insufficient to meet the requirements for greater power transmission capacity and the increasing transmission distances between power generation and load centres[7]. Consequently, China focused on constructing 500 kV extra-high voltage (EHV) transmission systems and 1000 kV AC and ±800 kV DC ultra-high voltage (UHV) transmission systems in the past decade, mainly to enhance inter-provincial power transmission and to optimize renewable power resources. Thus, the proportion of transmission systems with higher voltage classes increased, resulting in their increasing shares in the GHG emissions structure. In particular, UHV transmission systems, as the core of the global energy interconnection strategy, have experienced rapid development since 2008 (Supplementary Tables 2–4). Approximately 1/3 of the new increases in GHG emissions were attributable to UHV systems in 2017, and by the end of 2017, the percentages of cumulative GHG emissions of UHV AC and DC systems were 2.5% (22 Mt) and 3.0% (27 Mt) of the total, respectively.

Emission gaps between provincial regions

The cumulative GHG emissions embodied in provincial power transmission systems also show dramatic changes after 1990 (Supplementary Tables 5–9). Liaoning (12 Mt), Hubei (8.9 Mt), Jiangsu (7.5 Mt), and Shandong (7.3 Mt) were the top four contributors and were responsible for 10%, 7%, 6%, and 6% of the national total in

1990, respectively, while Hainan, Tibet, Xinjiang, Ningxia, and Qinghai together contributed merely 2% (Fig. 2a). In particular, no transmission facilities above 220 kV were built in 1990 in Tibet and Hainan.

Around 2000, the Chinese government launched the Great Western Development Strategy whose key goal was to make breakthroughs in infrastructure construction, including power transmission facilities. An important national strategy called the West-East Power Transmission Project was launched and targeted at promoting national power distribution as well as developing western areas. Because of this project, the cumulative GHG emissions embodied in the western provincial regions increased by 0.23 Gt from 1990 to 2017 (Fig. 2b). Conversely, the share of cumulative emissions caused by the Northeast China Grid (Liaoning, Jilin and Heilongjiang) decreased by 10%. The Gini coefficient of cumulative GHG emissions decreased from 0.46 in 1990 to 0.35 in 2017 while that of cumulative GHG emissions per capita decreased from 0.37 in 1990 to 0.29 in 2017 (Fig. 2g). These gradually decreasing Gini coefficients suggest that the national power transmission system is becoming more balanced.

Despite the Western Region Development Strategy, power transmission system construction in the western regions still lags far behind that in the eastern regions. The richer eastern provincial regions have higher cumulative GHG emissions per unit area (km^2) whereas the opposite situation is occurring in the less-developed western regions. For example, the cumulative GHG emissions per unit area in Shanghai were 3600 t/km^2 in 2017, which was approximately 4,200 times that of Tibet (0.86 t/km^2), which had the lowest emissions per unit area in the same year (Fig. 2d). In particular, the three megacities, namely, Shanghai, Tianjin, and Beijing, maintained the top three positions from the perspective of emissions per unit area (Fig. 2c). A large gap resulted from the differences between provincial territories and the disparities in power transmission infrastructure distribution. For example, 15,029 km of transmission lines were located in Shaanxi along with 77 substations with a capacity of 62.95 GVA in 2017 while 42,471 km of transmission lines and 724 substations with a capacity of 371.64 GVA were located in Jiangsu, although the territory of Shaanxi is twice as large as that of Jiangsu.

However, the GHG emissions per capita of each province are different (Fig. 2e, Fig. 2f). Qinghai, Inner Mongolia, and Ningxia were the provinces with the highest cumulative GHG emissions per capita with a value of 2.0 t/person, 1.8 t/person, and 1.7 t/person, respectively, while Hainan had the lowest cumulative emissions per capita with 0.29 t/person (Fig. 2f). This result is mainly because Qinghai, Inner Mongolia, and Ningxia occupy 20% of China's land area but have only 2.7% of the total population. To achieve the government's goal of providing electricity to everyone in China, a large number of power transmission facilities have been built. As for Hainan Province, its population density of is 264.57 people/km^2, which is much higher than that of Qinghai Province (8.27 people/km^2). Additionally, due to the small scale of secondary industry in Hainan Province, the power demand is extremely low, and the construction of power infrastructure is less intensive than that in areas with the secondary industry as the pillar.

Factors influencing the embodied GHG emissions

The GHG emissions of power transmission projects are determined by different factors. For transmission lines, the voltage class, terrain (the descriptions of different terrains are shown in Supplementary Table 10), and GHG intensity of the inputs are important influential factors. The GHG emissions embodied in transmission lines per kilometre increase when the voltage class rises because higher voltage lines require more products such as cables and steel. In 2017, the average GHG emissions embodied in transmission lines per kilometre for each voltage class were 0.19 kt (220 kV), 0.21 kt (330 kV), 0.39 kt (500 kV), 0.56 kt (750 kV), and 1.0 kt (1,000 kV) (Supplementary Table 11). However, DC transmission lines are an exception. The average emissions for ±800 kV DC power lines per kilometre were 0.46 kt in 2017 (Supplementary Table 12), well below that of even the 750 kV AC lines. This difference occurs because per kilometre DC transmission lines consume much less material (e.g., wires) than AC lines of a similar voltage class[28].

Terrain also plays an important role in the GHG emissions embodied in transmission lines. Transmission lines per kilometre in high mountains and river swamps induce the largest amounts of GHG emissions, followed by those in mountainous areas and deserts (Fig. 3a), as more transportation services are required in such areas. Transmission lines per kilometre in flatlands and hills induce the lowest GHG emissions. As shown in Fig. 3b, steel products, construction, overhead transmission lines and ground wires are the main sources of GHG emissions embodied in transmission line projects; these sources are responsible for approximately 93% of the total. Among these sources, steel products, which are important components of power transmission towers and foundation engineering, contributed the most. For more details regarding the GHG emissions embodied in the major components of transmission line projects, please refer to Supplementary Tables 13–14.

For substations, the voltage class, set number and nameplate capacity of transformers and the GHG intensity of the inputs are identified as important influential factors (Supplementary Tables 15–16). As the voltage class increases, more electrical equipment and construction engineering are required, thus leading to more embodied GHG emissions (Fig. 4a). The estimated average embodied GHG emissions of all 1,000 kV projects are 320 kt (the highest)—more than 20 times greater than that of 220 kV projects (the lowest). Similarly, along with the growing set number and nameplate capacity of transformers, a substation's GHG emissions also increase due to the demand for more equipment inputs. In addition, for the same voltage class, substations embody more GHG emissions when transformers with larger nameplate capacities are installed (Fig. 4a).

It should be noted that, due to the scale effect, increasing the nameplate capacity or the set number of transformers reduces a substation project's per-capacity GHG emissions. In contrast to transmission lines, a DC converter station (±800 kV) is more GHG-intensive than an AC substation in a similar voltage class. This is because the DC converter station requires more auxiliary equipment such as a valve hall and a converter transformer for AC-DC converter.

Electrical equipment, cable and overhead lines, and construction are the top three contributors to the embodied GHG emissions of AC substation and DC converter station projects (Supplementary Tables 17–18). Fig. 4b shows that when the voltage class increases, the proportions of embodied GHG emissions from electrical equipment dramatically increase—from 51% (average proportion for 220 kV projects) to 74% (average proportion for 1,000 kV projects). In contrast, the shares of GHG emissions from construction decrease from 39% for 220 kV projects to 21% for 1,000 kV projects.

Embodied GHG emissions per unit of power transmission

This section further analyses and compares the embodied GHG emissions per unit from various power transmission units under 4 different scenarios. Generally, a typical power transmission unit consists of transmission lines and at least two substations or converter stations. Scenario 1 assumes that the transmission units operate at the theoretical maximum transmission distances while Scenario 2 uses the actual transmission distances. In Scenarios 3 and 4, the power transmission units operate at the theoretical maximum and actual transmission distances and capacities, respectively. Note that Scenarios 2 and 4 refer only to ±800 kV UHV DC and 1,000 kV UHV AC systems because the actual distances and actual nominal capacities of systems with other voltage classes are missing.

Under Scenario 1, the GHG emissions per km increase when the voltage class increases (Table 1) as higher voltage transmission lines and substations require more GHG-intensive products such as steel and equipment. Compared with Scenario 2, the

±800 kV DC and 1,000 kV AC GHG emissions per km under Scenario 1 are 27% and 48% lower, respectively, reflecting that ±800 kV DC transmission units are closer to the theoretical maximum condition.

Under Scenario 3, GHG emissions per km·MW decrease as the voltage class rises, indicating that the higher voltage class requires more materials or inputs for both the AC and DC transmission system units. Because the actual nominal capacities and distances of already-built power transmission systems are much smaller and shorter than the maximum conditions (Supplementary Table 19), if the voltage class is the same, the GHG emissions per km·MW under Scenario 4 are overwhelmingly higher than those under Scenario 3. In addition, the DC transmission system has the smallest amount of emissions in both Scenarios 3 and 4.

Discussion and policy implications

The current study reveals that the decreasing GHG emission intensities of China's economic sectors have made remarkable contributions to GHG mitigation for power transmission construction. If the intensities had remained at 1990 levels, the GHG emissions induced by China's power transmission infrastructure would have tripled during the study period. Therefore, the decarbonisation of transmission infrastructure will continue to benefit from China's unremitting efforts to develop a low-carbon economy. In addition, the rate of depreciation is verified as a key parameter that affects the embodied GHG emissions induced by power transmission infrastructure. Monte Carlo simulation shows that if the depreciation rate is reduced to the minimum range specified by the National Development and Reform Commission

(NDRC)[29] of China, the cumulative GHG emissions embodied in power transmission infrastructure construction would decrease by 7.6% in 2017. It is worth noting that reducing the depreciation rate by extending the service life of transmission infrastructure will lead to line ageing, causing more power loss. On the other hand, building new infrastructure will produce a large amount of emissions, as shown by our results. Therefore, a trade-off between building new transmission infrastructure and extending the service life of existing infrastructure must be made.

The results show that the western regions are characterized as having high GHG emissions per capita but low GHG emissions per unit area. This is because the Chinese government and power grid enterprises have built an extensive power transmission infrastructure in the western provincial regions to meet the power demand in remote areas and export the renewable energy in the western region through electricity. China's power transmission infrastructure has provided a stable power supply for more than a billion people; however, it may not be an environmentally friendly choice for some regions with very low population density in China. As many areas in Western China are endowed with abundant indigenous renewable energy resources, the energy consumption by local residents can instead be satisfied by establishing distributed energy generation systems and microgrids, which will subsequently reduce the GHG emissions caused by large-scale power transmission infrastructure construction.

Cost control and rational investment in transmission lines and substations are also crucial for reducing GHG emissions from transmission systems. When the transmission price is calculated using the method of "permitted cost plus reasonable income", power grid enterprises may expand their total assets by overinvesting in high-voltage power infrastructure without considering regional power demand, and these measures will also bring about substantial GHG emissions increases. According to the regulatory report from the NDRC and the National Energy Administration (NEA)[29], investments and costs of power transmission infrastructure construction should be strictly monitored and controlled by the following measures: (1) improved reference cost standards for different types of transmission lines and substations are set as benchmarks for cost control; (2) a maximum cost is set for the material, repair, and miscellaneous expenses of infrastructure construction; and (3) costs caused by overinvestment in power transmission infrastructure cannot be considered in the power purchase price.

Moreover, improving the utilization efficiency also prevents additional GHG emissions induced by power transmission infrastructure construction. According to a regulatory report on power grid projects[30], approximately 1/3 of power transmission systems' capacities fail to meet their design standards. The notable differences between Scenarios 3 and 4 indicate that there is still a genuine need to reduce GHG emissions from power transmission infrastructure.

Incentivized by global energy interconnection with UHV as its core[7,31], China is still investing in power transmission infrastructure at home and abroad. In February 2020, the Chinese government once again emphasized the need to accelerate the construction of infrastructure such as UHV[32]. Consequently, GHG emissions from infrastructure construction are expected to increase significantly. Therefore, policies are urgently needed to promote the low-carbon development of the currently carbon-intensive power transmission infrastructure. Until now, the GHG emissions in power infrastructure construction have been underestimated, hindering the decarbonisation of current GHG-intensive power infrastructure construction. To address this problem, the government is encouraged to set GHG emissions criteria for power transmission infrastructure construction based on comprehensive emissions accounting as conducted in this study based on the latest comprehensive input inventory and updated time series GHG emission intensities. Such emissions criteria can help power grid enterprises choose more low-carbon products and equipment, which will incentivize the upstream equipment manufacturers and raw material enterprises to achieve low-carbon and cleaner production. Finally, while the scope of this study focused on China's power transmission infrastructure, the assessment framework can also be applied to global infrastructure such as energy, transportation and telecommunications infrastructure.

However, as an initial attempt, the current study has several limitations, which must be addressed in future works. For example, only the emission intensities in the period from 1995 to 2015 are available. The ordinary least squares model was applied to estimate the emission intensities of the missing years, which caused uncertainty (see Supplementary Table 23). Additionally, the inputs of products were aggregated to match the IO sectors' emission intensities (for example, the main transformer, power distribution device, power cable and control cables are products from sectors that manufacture electrical machinery and apparatus), which may lead to aggregation bias. In our future work, the operation and maintenance processes of power transmission infrastructure will be covered to evaluate the impact of power loss. By doing so, we will be able to draw a more comprehensive and complete picture.

Methods

Embodied GHG emissions of power transmission projects. A hybrid method that employs a combination of process analysis and input-output analysis has been successfully applied in many studies to investigate the environmental impact of power generation systems[33] and renewable energy projects[34,35]. The first step of this hybrid method is to obtain the embodied GHG emission intensities as the inputs. Based on the direct emissions inventory, an environmentally extended input-output analysis (EEIOA)[36,37] is adopted to calculate the emission intensities, which are expressed as:

$$e_t = E_t(\hat{X}_t - Z_t)^{-1} \quad (1)$$

where e_t is a $1 \times N$ matrix that represents the embodied GHG emission intensities of different sectors in year *t'*; E_t is a $1 \times N$ matrix of the direct GHG emissions of different sectors in year t'; $\hat{X}_t$ is the diagonal matrix of total output vectors; and Z_t is the intermediate input matrix. The EXIOBASE input-output tables are used in this study; therefore, the embodied emission intensities and the embodied emissions are calculated based on monetary units.

Because the emission intensities calculated by EXIOBASE are available only for the period from 1995 to 2015, we established a multiple regression with the available data in year t' as an explanatory variable as follows:

$$\ln E_{K,t'} = \beta_1 \ln t' + con + \varepsilon \tag{2}$$

The coefficients β_1 and constant terms con can be estimated by Stata; the R^2 values of most estimation equations are above 0.82. Then, the embodied GHG emission intensities of every industrial sector in the years t without IO tables are estimated as follows:

$$e_{i,t'} = e^{(\beta_1 \ln t + con)} \tag{3}$$

Second, we compiled an exhaustive input inventory for power transmission infrastructure. We classified the enormous number of inputs into different sectors according to the industrial classification standard of EXIOBASE. With the emission intensity and classified input data, the embodied GHG emissions of typical AC and DC overhead transmission line projects in year t ($E_{TL,t}$) can be calculated by

$$E_{TL,t} = \sum_i C_{i,t} \times e_{i,t} \tag{4}$$

where $C_{i,t}$ is the input to the product of sector i in year t and $e_{i,t}$ is the corresponding embodied GHG intensity of that sector. The embodied GHG emissions per kilometre of typical AC and DC transmission line projects in year t ($E_{K,t}$) can be obtained by

$$E_{K,t} = E_{TL,t} / D_{TL} / n_{TL} \tag{5}$$

where D_{TL} is the length of a typical transmission line project and n_{TL} is the number of circuits in typical transmission line projects.

The average embodied GHG emissions per kilometre of transmission lines crossing different terrains p under voltage v in year t ($\overline{E_{K,t}^{v,p}}$) can be obtained by

$$\overline{E_{K,t}^{v,p}} = \sum_{mt} \left(E_{K,t}^{v,p} / mt \right) \quad (6)$$

where $E_{K,t}^{v,p}$ is the embodied GHG emissions per kilometre of typical transmission line projects under voltage v in year t and mt is the quantity of typical transmission line projects across terrain p under voltage v in year t.

The embodied GHG emissions of typical AC substation and DC converter station projects ($E_{S,t}$) are investigated by the same method. Then, the embodied GHG emissions per nameplate capacity of typical AC substation and DC convertor station projects in year t can be obtained by

$$E_{C,t} = E_{S,t} / NC_S / ns \quad (7)$$

where NC_S is the nameplate capacity of the main transformers of typical projects and n_s is the set number of main transformers of typical projects. The average embodied GHG emissions per nameplate capacity of AC substation and DC convertor station projects under voltage v ($\overline{E_{C,t}^{v}}$) can be calculated by

$$\overline{E_{C,t}^{v}} = \sum_{j} E_{S,t}^{v} / \sum_{j} NC_S^{v} \quad (8)$$

where $E_{s,t}^{v}$ is the embodied GHG emissions per nameplate capacity of AC substation and DC convertor station projects under voltage v in year t and j is the quantity of typical projects under voltage v.

Provincial cumulative embodied emissions. Based on the GHG emission inventory of transmission lines and substation projects, we can further estimate the GHG emissions of China's transmission system. The average embodied GHG emissions per kilometre of provincial region r's transmission lines under voltage v in year t ($\overline{E_{K,t}^{v,r}}$) can be obtained by

$$\overline{E_{K,t}^{v,r}} = \sum_{k} \overline{E_{K,t}^{v,p}} \times PT_{p,r} \tag{9}$$

where $PT_{p,r}$ is the proportion of terrain p in provincial region r and k is the number of transmission line projects under voltage v in terrain p. In this study, the proportions of various terrains in different provincial regions of China such as flatland, hill, mountainous area, desert, and river swamp are estimated based on the Thematic Database for Human-Earth System[38]. Because transmission lines in mountainous areas and high mountains are not distinguished in the Thematic Database, this research applied a digital elevation model (DEM)[39] and ArcGIS 9.2 to calculate the ratio of mountainous area to high mountains.

The newly increased length of transmission lines ($¿n_t^{v,r}$) and nameplate capacity of substations ($NC_t^{v,r}$) under voltage v in provincial region r and year t can be expressed as follows:

$$¿n_t^{v,r} = TLen_t^{v,r} - \left(1 - \alpha_{TL}^{v}\right) TLen_{t-1}^{v,r} \tag{10}$$

$$NC_t^{v,r} = TNC_t^{v,r} - \left(1 - \alpha_{S}^{v}\right) TNC_{t-1}^{v,r} \tag{11}$$

where $TLen_t^{v,r}$ and $TLen_{t-1}^{v,r}$ are the total lengths of the transmission lines in provincial region r under voltage v in years t and $t-1$, respectively; $NC_t^{v,r}$ and $TNC_{t-1}^{v,r}$ are the total nameplate capacities of the substations in provincial region r under voltage v in years t and $t-1$, respectively; and α_{TL}^{v} and α_{S}^{v} are the average depreciation rates of transmission lines and substations under voltage v, respectively.

The cumulative embodied GHG emissions of the power transmission system of provincial region r in year t (CE_t^r) can be calculated as follows:

$$CE_t^r = \sum_t \sum_m \overline{E_{K,t}^{v,r}} \times \leq n_t^{v,r} + \sum_t \sum_m \overline{E_{C,t}^{v}} \times NC_t^{v,r} \tag{12}$$

where m is the quantity of voltage classes in the power transmission system of provincial region r in year t.

We use 1990 embodied GHG emission intensities and China's transmission infrastructure data to estimate the cumulative emissions in 1990. We use this method to estimate the cumulative emissions in 1990 considering that the scale of the transmission infrastructures before 1990 was relatively small. For example, the length of 220 kV and above transmission lines in 1990 was only 13% of that in 2017. More importantly, the data on transmission line length and substation installed capacity before 1990 are not available. Given this information, it should be noted that the cumulative GHG emissions in 1990 may be underestimated because China's GHG emission intensities before 1990 are higher than that of 1990.

Scenario analysis. A power transmission unit consisting of transmission lines and 2 substations or converter stations can be considered the smallest power transmission system. A real power transmission system comprises a certain number of units. Here, we conduct an analysis of GHG emissions by a power transmission unit under different scenarios. In Scenario 1, the transmission unit operates at the theoretical maximum transmission distance while in Scenario 2, the power transmission unit operates at the actual transmission distance. The embodied GHG emissions per kilometre of AC and DC power transmission units under voltage v (E_P^v) (Scenarios 1 and 2) can be expressed as follows:

$$E_P^v = \left(\overline{E_{K,t}^v} \times L_{td}^v + 2 \times \overline{E_{C,t}^v}\right) / L_{td}^v \tag{13}$$

where L_{td}^v is the theoretical maximum transmission distance (Scenario 1) or the actual transmission distance (Scenario 2) of the power transmission unit under voltage v. On this basis, the embodied GHG emissions per kilometre and the capacity of AC and DC power transmission units under voltage v (E_{PC}^v) (Scenario 3 and 4) can be obtained by

$$E_{PC}^v = E_P^v / TC^v \tag{14}$$

where TC^v is the theoretical maximum transmission capacity (Scenario 3) or the actual nominal transmission capacity (Scenario 4) of the power transmission unit under voltage v.

Uncertainty analysis

The uncertainties of the GHG footprint in this study originate from three major sources, specifically, the input inventories, GHG emission intensities and depreciation rate of the power transmission infrastructure. Here, we adopted error propagation to estimate the overall uncertainties[40]. Specifically, stochastic modelling based on Monte Carlo simulation was used to propagate the error in terms of the standard deviation (SD)[41,42]. We define the order of magnitude of each source data x as lg$x$. Then, the absolute error of lg$x$ can be approximated as:

$$d(lg\,x) \approx lg(x + dx) - lg\,x = lg\left(1 + \frac{dx}{x}\right) = lg\,(1 + Rx) \tag{15}$$

where dx is the SD of x and Rx represents the relative SD (RSD) of x. Then, the perturbation of x (denoted as x^P) satisfies the following equation:

$$lg\left(x^p\right) \approx lg\,x + d\left(lg\,x\right) = lg\,x + lg\ \left(1 + Rx\right) \quad (16)$$

Thus, the Monte Carlo perturbation could be carried out for each data element to obtain the perturbed GHG emission inventory E^P, intermediate matrix Z^P and final demand matrix Y^P. The perturbed X^P can be obtained by summing Z^P and Y^P to maintain the balance of the IO table. A 3% threshold was set to exclude over-perturbation[43]. It should be noted that the observations of MRIO entries follow a lognormal distribution to avoid sign changes in Monte Carlo perturbations[44]. The perturbation was conducted for 10000 iterations, from which the overall SD of the GHG footprint could be derived. For the cumulative GHG emissions, another influencing factor is the depreciation rate of transmission lines and substations. We assume that the depreciation rate follows a normal distribution. For further technical details and the RSDs of different raw data, see Supplementary Method and Supplementary Tables 20–21.

Data sources

In this study, the MRIO database EXIOBASE was applied to calculate GHG emission intensities[45,46]. With 200 commodities and 163 industries, of which 33 represent the primary sectors of the economy, EXIOBASE provides the highest consistent level of product and sector detail by country among all currently available MRIO models[47], and we have matched the sectors of EXIOBASE tables with the product/service input categories of this study (Supplementary Table 22). It should be noted that the study did not differentiate the GHG emission factors for each provincial region in China, as the EXIOBASE MRIO tables are on the national scale.

China's power transmission system is dominated by overhead transmission line projects; however, there are also a few exceptions. For example, the 500 kV cross-sea interconnection project between Hainan and Guangdong crossing the Qiongzhou Strait uses submarine cable. The input inventories of different overhead transmission lines and substation and converter station projects[48] were derived from the State Grid Corporation of China (SGCC)[49]. However, cable transmission line projects were not considered by this study due to the lack of data. The data on total transformer nameplate capacity, converter transformer capacity, and the total AC and DC transmission line circuit lengths in each provincial region from 1990 to 2017 were derived from the Annual Compilation of Statistics for Power Industry[25]. However, because the statistics for 1992 were unavailable, this research used interpolation to estimate the missing data. The average depreciation rate intervals of transmission lines and substations were collected from the NDRC[29]. The theoretical maximum transmission distance and transmission capacity of each voltage class were those reported by Liu[7].

Data availability

All the GHG emission inventories of power transmission projects and China's 31 provincial regions' power transmission systems from 1990 to 2017 are listed in Supplementary Tables 5–18. All our data are available to readers and can be freely downloaded from the CEADs website (https://www.ceads.net/data/process/).

Code availability

The code for uncertainty analysis can be accessed via our recent work published in Scientific Data (https://doi.org/10.1038/s41597-020-00662-4), or https://www.ceads.net/data/process/.

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Acknowledgements

W.W. was supported by the National Key R&D Program of China (2019YFC1908501), the National Natural Science Foundation of China (72088101, 71904125, and 71690241), and the

Shanghai Sailing Program (18YF1417500). J.L. was supported by the National Natural Science Foundation of China (72074137 and 71961137010), and the Taishan Scholars Program. K.F. was supported by the Taishan Scholars Program and the Shandong University Interdisciplinary Research and Innovation Team of Young Scholars. N.Z. was supported by the National Natural Science Foundation of China (72033005).

Competing interests

The authors declare no competing interests.

Author contributions

W.W., J.L., D.G., and N.Z. conceived the study. H.Q. and K.F. provided the data. W.W., J.L., B.C., M.W., and P.Z. performed the analysis. All authors (W.W., J.L., B.C., M.W., P.Z., D.G., J.M., H.Q., Y.C., C.K., K.F., Q.Y., N.Z., X.L., and J.X.) interpreted the data. W.W. and J.L. prepared the manuscript. All authors (W.W., J.L., B.C., M.W., P.Z., D.G., J.M., H.Q., Y.C., C.K., K.F., Q.Y., N.Z., X.L., and J.X.) revised the manuscript.

Figure Legends

Fig. 1 | Embodied GHG emissions induced by China's power transmission infrastructure. Total cumulative embodied GHG emissions from different voltage classes from 1990 to 2017. The shares of cumulative embodied GHG emissions from different voltage classes and infrastructure types in 1990 and 2017.

Fig. 2 | Evolution of cumulative GHG emissions embodied in the power transmission infrastructure of different provincial regions. The cumulative embodied GHG emissions of different provincial regions in (a) 1990 and (b) 2017. The cumulative embodied GHG emissions per unit area of different provincial regions in (c) 1990 and (d) 2017. The cumulative embodied GHG emissions per capita of different provincial regions in (e) 1990 and (f) 2017. (g) The Gini coefficient of embodied GHG emissions per capita from 1990 to 2017.

Fig. 3 | Embodied GHG emissions of typical transmission line projects in 2017. (a) Embodied GHG emissions per kilometre of typical AC and DC transmission line projects. The 6 frames arranged vertically show the embodied GHG emissions per kilometre of transmission line projects for different voltage classes. In each frame, the boxes of different colours represent the embodied GHG emissions per kilometre of projects under certain terrain conditions. (b) The average embodied GHG emissions per kilometre and emission structures of typical AC and DC transmission line projects. A box plot shows the range of embodied GHG emissions for typical transmission line projects under a certain terrain condition. The upper half of the box spans the first quartile to the second quartile, and the lower half of the box spans the second quartile to the third quartile. The upper point indicates the maximum value, the middle point indicates the average value, and the lower point indicates the minimum value.

Fig. 4 | Embodied GHG emissions of typical substation projects in 2017. (a) Total embodied GHG emissions of typical AC substation and DC converter station projects. The boxes of different colours represent the total embodied GHG emissions of projects for a certain voltage class and nameplate capacity. (b) Average embodied GHG emissions and emission structure of typical AC substation and DC converter station projects. A box plot shows the range of embodied GHG emissions for typical transmission line projects under a certain terrain condition. The upper half of the box spans the first quartile to the second quartile, and the lower half of the box spans the second quartile to the third quartile. The upper point indicates the maximum value, the middle point indicates the average value, and the lower point indicates the minimum value.

Tables

Table 1. Embodied GHG emissions of power transmission units under different scenarios[a]

	AC transmission system unit					DC transmission system unit
	220 kV	330 kV	500 kV	750 kV	1000 kV	±800 kV
Scenario 1 (t CO_2 eq./km) [b]	280	280	490	690	1400	1100
Scenario 2 (t CO_2 eq./km) [c]	- [d]	- [d]	- [d]	- [d]	2000	1400
Scenario 3 (t CO_2 eq./km·MW) [b]	0.94	0.35	0.33	0.28	0.22	0.14
Scenario 4 (t CO_2 eq./km·MW) [c]	- [d]	- [d]	- [d]	- [d]	0.31	0.19

[a] The embodied GHG emissions are based on typical transmission infrastructure projects in 2017.

[b] The theoretical maximum transmission distance and transmission capacity for each voltage class are derived from Liu[7].

[c] The actual transmission distance and actual nominal transmission capacity for ±800 kV DC and 1,000 kV AC systems are calculated using data from the National Energy Administration, State Grid Corporation of China and China Southern Power Grid Company Limited (Supplementary Tables 2-3).

[d] "-" represents no data.