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Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure

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31 **Abstract**

32 China has built the world's largest power transmission infrastructure by consuming
33 massive volumes of greenhouse gas (GHG)-intensive products such as steel. A
34 quantitative analysis of the carbon implications of expanding the transmission
35 infrastructure would shed light on the trade-offs among three connected dimensions of
36 sustainable development, namely climate change mitigation, energy access and
37 infrastructure development. By collecting a high-resolution inventory, we developed
38 an assessment framework of, and analysed, the GHG emissions caused by China's
39 power transmission infrastructure construction during 1990–2017. We show that
40 cumulative embodied GHG emissions have dramatically increased by more than 7.3
41 times those in 1990, reaching 0.89 Gt CO₂ eq. in 2017. Over the same period, the gaps
42 between the well-developed eastern and less-developed western regions in China have
43 gradually narrowed. Voltage class, transmission line length and terrain were important
44 factors that influenced embodied GHG emissions. We discuss measures for the
45 mitigation of GHG emissions from power transmission development that can inform
46 global low-carbon infrastructure transitions.

47

48 In recent decades, China's power transmission infrastructure has experienced
49 rapid development^{1,2}, mainly driven by the enormous electricity consumption³ that has
50 occurred against a backdrop of the long distances between power generation and load
51 centres⁴. To guarantee a reliable power supply, vast amounts of money and other
52 resources have been devoted to the construction of China's power transmission

53 infrastructure. In 2017 alone, 78.7 billion USD was spent on power transmission
54 construction⁵. Given this unprecedented level of expenditure, China now possesses
55 the world's largest power transmission infrastructure⁶. Its transmission lines with
56 voltage classes over 220 kV reached 6.87E+05 km in 2017, approximately twice that
57 of Europe⁷. Notably, China's power transmission infrastructure will be expanded in
58 the foreseeable future motivated by the demand to meet fast-growing renewable
59 power^{8,9} and ambitious strategies such as global energy interconnection¹⁰.

60 The construction of infrastructure has profoundly harmful environmental
61 impacts¹¹⁻¹³, and power transmission infrastructure is no exception. China's great
62 achievement in power transmission infrastructure has been gained at the cost of
63 consuming substantial amounts of greenhouse gas (GHG)-intensive inputs such as
64 steel, which produce a large amount of GHG emissions via their supply chains^{14,15}.
65 Nevertheless, only a handful of studies have made initial attempts to analyse the GHG
66 emissions resulting from regional power transmission infrastructure in several
67 developed countries^{16,17}. These studies have suggested that power transmission
68 systems have great impacts on global climate change; however, these studies have
69 been limited due to a lack of a comprehensive and systematic investigation. First, the
70 focus of the previous studies has been confined to specific components of the whole
71 power transmission infrastructure such as overhead lines, underground cables^{18,19},
72 transformers, and substation equipment²⁰. Second, the consideration of important
73 inputs such as communication and auxiliary power equipment has been missing.
74 Finally, the factors that influence the GHG emissions induced by power transmission

75 infrastructure, specifically, voltage class and terrain conditions, have not been
76 identified.

77 In this study, we have developed an assessment framework that, for the first time,
78 provides a holistic picture of embodied GHG emissions from China's large-scale
79 power transmission construction during the period from 1990 to 2017. We began by
80 compiling a detailed inventory of the national power transmission system. The dataset
81 includes information on more than 10,000 types of input for 191 typical power
82 transmission infrastructure projects comprising 145 types of alternating current (AC)
83 overhead transmission line project, 37 typical AC substation projects, 8 typical direct
84 current (DC) overhead transmission line projects and 1 typical DC convertor station
85 project. The detailed input inventory of all the projects investigated by this study can
86 be found on our dataset websites²¹. We then calculated the annual addition and the
87 cumulative GHG emissions (defined as the sum of the annual addition emissions)
88 from China's national power transmission infrastructure construction using a hybrid
89 method as a combination of process analysis and input-output analysis^{22,23}. We also
90 assessed the impact of some important factors, such as transmission line length and
91 nameplate capacity, on the embodied GHG emissions (nameplate capacity is also
92 known as nominal capacity, rated capacity or installed capacity, referring to the
93 conventional value of apparent power under principal tapping). We analysed the
94 emission uncertainty using Monte Carlo simulation (see the Methods section) by
95 considering the uncertainties from GHG emission intensities, input inventories, and
96 the depreciation rate of the power transmission infrastructure. We also make a

97 comparison with the existing research using life cycle assessment (LCA) (see the
98 Supplementary Information - Comparison with previous research) to verify the
99 robustness of this assessment framework. Additionally, we estimated China's
100 provincial GHG emissions induced by power loss (see the Supplementary Information
101 - The GHG emissions of power loss), which has been recognized as the major
102 contributor to the GHG emissions from power transmission²⁴. By comparing with
103 GHG emissions induced by power loss, we can have a more comprehensive
104 understanding of the scale of embodied GHG emissions from power transmission
105 infrastructure.

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

116 **Rapidly growing cumulative embodied GHG emissions**

117 In 1990, the cumulative embodied GHG emissions induced by China's power
118 transmission system were 0.12 Gt. In 2017, this figure had dramatically increased by

119 more than 7.3 times and reached 0.89 Gt (Fig. 1). Among these emissions, substation
120 and transmission line infrastructure account for 0.46 Gt and 0.43 Gt, respectively.
121 These growing cumulative emissions are mainly attributable to China's vast
122 investment in the national power transmission infrastructure²⁵. The majority of the
123 investment has been used to purchase GHG-intensive products such as electrical
124 equipment to build power transmission infrastructure²⁶. Notably, approximately 90%
125 of the total GHG emissions are from four economic sectors (**Manufacture** of basic
126 iron and steel and of ferro-alloys and first products thereof; **Manufacture** of fabricated
127 metal products, except machinery and equipment; Manufacture of electrical
128 machinery and apparatus, **nec**; and Construction). By contrast, China's decreasing
129 embodied GHG emission intensities (Supplementary Figure 1) contributed to a
130 remarkable amount of emission reduction from infrastructure construction. In
131 particular, the GHG emission intensities of the metallurgy, electrical equipment, and
132 construction sectors, as the major suppliers of power transmission systems, decreased
133 by 76%, 81% and 76% from 1990 to 2017, respectively, due to China's progress in
134 energy efficiency improvements and energy structure adjustments. Meanwhile, the
135 uncertainties of the annual embodied GHG emissions caused by power infrastructure
136 were approximately -14% and +19% at the 95% level of confidence during the period
137 from 1995 to 2015 (detailed results are presented in Supplementary Table 1).

138 The structure of GHG emissions embodied in transmission projects with
139 different voltages shows remarkable changes (Fig. 1). In 1990, 220 kV
140 overwhelmingly dominated the cumulative GHG emissions while 330 kV and 500 kV

141 accounted for only minor shares. In the early 1990s, coal transportation played a
142 central role in inter-provincial energy transmission, and 220 kV systems could satisfy
143 the power transmission needs that occurred mainly within each provincial region²⁷.
144 However, the 220 kV systems gradually became insufficient to meet the requirements
145 for greater power transmission capacity and the increasing transmission distances
146 between power generation and load centres⁷. Consequently, China focused on
147 constructing 500 kV extra-high voltage (EHV) transmission systems and 1000 kV AC
148 and ± 800 kV DC ultra-high voltage (UHV) transmission systems in the past decade,
149 mainly to enhance inter-provincial power transmission and to optimize renewable
150 power resources. Thus, the proportion of transmission systems with higher voltage
151 classes increased, resulting in their increasing shares in the GHG emissions structure.
152 In particular, UHV transmission systems, as the core of the global energy
153 interconnection strategy, have experienced rapid development since 2008
154 (Supplementary Tables 2–4). Approximately 1/3 of the new increases in GHG
155 emissions were attributable to UHV systems in 2017, and by the end of 2017, the
156 percentages of cumulative GHG emissions of UHV AC and DC systems were 2.5%
157 (22 Mt) and 3.0% (27 Mt) of the total, respectively.

158 **Emission gaps between provincial regions**

159 The cumulative GHG emissions embodied in provincial power transmission
160 systems also show dramatic changes after 1990 (Supplementary Tables 5–9). Liaoning
161 (12 Mt), Hubei (8.9 Mt), Jiangsu (7.5 Mt), and Shandong (7.3 Mt) were the top four
162 contributors and were responsible for 10%, 7%, 6%, and 6% of the national total in

163 1990, respectively, while Hainan, Tibet, Xinjiang, Ningxia, and Qinghai together
164 contributed merely 2% (Fig. 2a). In particular, no transmission facilities above 220 kV
165 were built in 1990 in Tibet and Hainan.

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

179 Despite the Western Region Development Strategy, power transmission system
180 construction in the western regions still lags far behind that in the eastern regions. The
181 richer eastern provincial regions have higher cumulative GHG emissions per unit area
182 (km^2) whereas the opposite situation is occurring in the less-developed western
183 regions. For example, the cumulative GHG emissions per unit area in Shanghai were
184 3600 t/km^2 in 2017, which was approximately 4,200 times that of Tibet (0.86 t/km^2),

185 which had the lowest emissions per unit area in the same year (Fig. 2d). In particular,
186 the three megacities, namely, Shanghai, Tianjin, and Beijing, maintained the top three
187 positions from the perspective of emissions per unit area (Fig. 2c). A large gap
188 resulted from the differences between provincial territories and the disparities in
189 power transmission infrastructure distribution. For example, 15,029 km of
190 transmission lines were located in Shaanxi along with 77 substations with a capacity
191 of 62.95 GVA in 2017 while 42,471 km of transmission lines and 724 substations with
192 a capacity of 371.64 GVA were located in Jiangsu, although the territory of Shaanxi is
193 twice as large as that of Jiangsu.

194 However, the GHG emissions per capita of each province are different (Fig. 2e,
195 Fig. 2f). Qinghai, Inner Mongolia, and Ningxia were the provinces with the highest
196 cumulative GHG emissions per capita with a value of 2.0 t/person, 1.8 t/person, and
197 1.7 t/person, respectively, while Hainan had the lowest cumulative emissions per
198 capita with 0.29 t/person (Fig. 2f). This result is mainly because Qinghai, Inner
199 Mongolia, and Ningxia occupy 20% of China's land area but have only 2.7% of the
200 total population. To achieve the government's goal of providing electricity to
201 everyone in China, a large number of power transmission facilities have been built. As
202 for Hainan Province, its population density of is 264.57 people/km², which is much
203 higher than that of Qinghai Province (8.27 people/km²). Additionally, due to the small
204 scale of secondary industry in Hainan Province, the power demand is extremely low,
205 and the construction of power infrastructure is less intensive than that in areas with
206 the secondary industry as the pillar.

207 **Factors influencing the embodied GHG emissions**

208 The GHG emissions of power transmission projects are determined by different
209 factors. For transmission lines, the voltage class, terrain (the descriptions of different
210 terrains are shown in Supplementary Table 10), and GHG intensity of the inputs are
211 important influential factors. The GHG emissions embodied in transmission lines per
212 kilometre increase when the voltage class rises because higher voltage lines require
213 more products such as cables and steel. In 2017, the average GHG emissions
214 embodied in transmission lines per kilometre for each voltage class were 0.19 kt (220
215 kV), 0.21 kt (330 kV), 0.39 kt (500 kV), 0.56 kt (750 kV), and 1.0 kt (1,000 kV)
216 (Supplementary Table 11). However, DC transmission lines are an exception. The
217 average emissions for ± 800 kV DC power lines per kilometre were 0.46 kt in 2017
218 (Supplementary Table 12), well below that of even the 750 kV AC lines. This
219 difference occurs because per kilometre DC transmission lines consume much less
220 material (e.g., wires) than AC lines of a similar voltage class²⁸.

221 Terrain also plays an important role in the GHG emissions embodied in
222 transmission lines. Transmission lines per kilometre in high mountains and river
223 swamps induce the largest amounts of GHG emissions, followed by those in
224 mountainous areas and deserts (Fig. 3a), as more transportation services are required
225 in such areas. Transmission lines per kilometre in flatlands and hills induce the lowest
226 GHG emissions. As shown in Fig. 3b, steel products, construction, overhead
227 transmission lines and ground wires are the main sources of GHG emissions
228 embodied in transmission line projects; these sources are responsible for

229 approximately 93% of the total. Among these sources, steel products, which are
230 important components of power transmission towers and foundation engineering,
231 contributed the most. For more details regarding the GHG emissions embodied in the
232 major components of transmission line projects, please refer to Supplementary Tables
233 13–14.

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

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

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

259 **Embodied GHG emissions per unit of power transmission**

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

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

273 ±800 kV DC and 1,000 kV AC GHG emissions per km under Scenario 1 are 27% and
274 48% lower, respectively, reflecting that ±800 kV DC transmission units are closer to
275 the theoretical maximum condition.

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

284 **Discussion and policy implications**

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

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

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

315 Cost control and rational investment in transmission lines and substations are
316 also crucial for reducing GHG emissions from transmission systems. When the

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

329 Moreover, improving the utilization efficiency also prevents additional GHG
330 emissions induced by power transmission infrastructure construction. According to a
331 regulatory report on power grid projects³⁰, approximately 1/3 of power transmission
332 systems’ capacities fail to meet their design standards. The notable differences
333 between Scenarios 3 and 4 indicate that there is still a genuine need to reduce GHG
334 emissions from power transmission infrastructure.

335 Incentivized by global energy interconnection with UHV as its core^{7,31}, China is
336 still investing in power transmission infrastructure at home and abroad. In February
337 2020, the Chinese government once again emphasized the need to accelerate the
338 construction of infrastructure such as UHV³². Consequently, GHG emissions from

339 infrastructure construction are expected to increase significantly. Therefore, policies
340 are urgently needed to promote the low-carbon development of the currently carbon-
341 intensive power transmission infrastructure. Until now, the GHG emissions in power
342 infrastructure construction have been underestimated, hindering the decarbonisation
343 of current GHG-intensive power infrastructure construction. To address this problem,
344 the government is encouraged to set GHG emissions criteria for power transmission
345 infrastructure construction based on comprehensive emissions accounting as
346 conducted in this study based on the latest comprehensive input inventory and
347 updated time series GHG emission intensities. Such emissions criteria can help power
348 grid enterprises choose more low-carbon products and equipment, which will
349 incentivize the upstream equipment manufacturers and raw material enterprises to
350 achieve low-carbon and cleaner production. Finally, while the scope of this study
351 focused on China's power transmission infrastructure, the assessment framework can
352 also be applied to global infrastructure such as energy, transportation and
353 telecommunications infrastructure.

354 However, as an initial attempt, the current study has several limitations, which
355 must be addressed in future works. For example, only the emission intensities in the
356 period from 1995 to 2015 are available. The ordinary least squares model was applied
357 to estimate the emission intensities of the missing years, which caused uncertainty
358 (see Supplementary Table 23). Additionally, the inputs of products were aggregated to
359 match the IO sectors' emission intensities (for example, the main transformer, power
360 distribution device, power cable and control cables are products from sectors that

361 manufacture electrical machinery and apparatus), which may lead to aggregation bias.
362 In our future work, the operation and maintenance processes of power transmission
363 infrastructure will be covered to evaluate the impact of power loss. By doing so, we
364 will be able to draw a more comprehensive and complete picture.

365

366 **Methods**

367 **Embodied GHG emissions of power transmission projects.** A hybrid method that employs a
368 combination of process analysis and input-output analysis has been successfully applied in many
369 studies to investigate the environmental impact of power generation systems³³ and renewable
370 energy projects^{34,35}. The first step of this hybrid method is to obtain the embodied GHG emission
371 intensities as the inputs. Based on the direct emissions inventory, an environmentally extended
372 input-output analysis (EEIOA)^{36,37} is adopted to calculate the emission intensities, which are
373 expressed as:

$$374 \quad e_t = E_t(\hat{X}_t - Z_t)^{-1} \quad (1)$$

375 where e_t is a $1 \times N$ matrix that represents the embodied GHG emission intensities of different
376 sectors in year t' ; E_t is a $1 \times N$ matrix of the direct GHG emissions of different sectors in year t' ;

377 \hat{X}_t is the diagonal matrix of total output vectors; and Z_t is the intermediate input matrix. The

378 EXIOBASE input-output tables are used in this study; therefore, the embodied emission
379 intensities and the embodied emissions are calculated based on monetary units.

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

382 explanatory variable as follows:

383
$$\ln E_{K,t} = \beta_1 \ln t' + con + \varepsilon \quad (2)$$

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

387
$$e_{i,t} = e^{(\beta_1 \ln t + con)} \quad (3)$$

388 Second, we compiled an exhaustive input inventory for power transmission infrastructure.
389 We classified the enormous number of inputs into different sectors according to the industrial
390 classification standard of EXIOBASE. With the emission intensity and classified input data, the
391 embodied GHG emissions of typical AC and DC overhead transmission line projects in year t (
392 $E_{TL,t}$) can be calculated by

393
$$E_{TL,t} = \sum_i C_{i,t} \times e_{i,t} \quad (4)$$

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

397
$$E_{K,t} = E_{TL,t} / D_{TL} / n_{TL} \quad (5)$$

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

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

402
$$\overline{E_{K,t}^{v,p}} = \sum_{mt} (E_{K,t}^{v,p}/mt) \quad (6)$$

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

406 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
 407 capacity of typical AC substation and DC converter station projects in year t can be obtained by

409
$$E_{C,t} = E_{S,t} / NC_S / n_s \quad (7)$$

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

413 be calculated by

414
$$\overline{E_{C,t}^v} = \sum_j E_{S,t}^v / \sum_j NC_S^v \quad (8)$$

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

418 **Provincial cumulative embodied emissions.** Based on the GHG emission inventory of
 419 transmission lines and substation projects, we can further estimate the GHG emissions of China's
 420 transmission system. The average embodied GHG emissions per kilometre of provincial region r 's

421 transmission lines under voltage v in year t ($\overline{E_{K,t}^{v,r}}$) can be obtained by

422
$$\overline{E_{K,t}^{v,r}} = \sum_k \overline{E_{K,t}^{v,p}} \times PT_{p,r} \quad (9)$$

423 where $PT_{p,r}$ is the proportion of terrain p in provincial region r and k is the number of
424 transmission line projects under voltage v in terrain p . In this study, the proportions of various
425 terrains in different provincial regions of China such as flatland, hill, mountainous area, desert,
426 and river swamp are estimated based on the Thematic Database for Human-Earth System³⁸.
427 Because transmission lines in mountainous areas and high mountains are not distinguished in the
428 Thematic Database, this research applied a digital elevation model (DEM)³⁹ and ArcGIS 9.2 to
429 calculate the ratio of mountainous area to high mountains.

430 The newly increased length of transmission lines ($\dot{i}n_t^{v,r}$) and nameplate capacity of

431 substations ($NC_t^{v,r}$) under voltage v in provincial region r and year t can be expressed as follows:

432
$$\dot{i}n_t^{v,r} = TLen_t^{v,r} - (1 - \alpha_{TL}^v) TLen_{t-1}^{v,r} \quad (10)$$

433
$$NC_t^{v,r} = TNC_t^{v,r} - (1 - \alpha_S^v) TNC_{t-1}^{v,r} \quad (11)$$

434 where $TLen_t^{v,r}$ and $TLen_{t-1}^{v,r}$ are the total lengths of the transmission lines in provincial region r

435 under voltage v in years t and $t-1$, respectively; $NC_t^{v,r}$ and $TNC_{t-1}^{v,r}$ are the total nameplate

436 capacities of the substations in provincial region r under voltage v in years t and $t-1$,

437 respectively; and α_{TL}^v and α_S^v are the average depreciation rates of transmission lines and

438 substations under voltage v , respectively.

439 The cumulative embodied GHG emissions of the power transmission system of provincial

440 region r in year t (CE_t^r) can be calculated as follows:

$$441 \quad CE_t^r = \sum_t \sum_m \overline{E_{K,t}^{v,r}} \times \leq n_t^{v,r} + \sum_t \sum_m \overline{E_{C,t}^v} \times NC_t^{v,r} \quad (12)$$

442 where m is the quantity of voltage classes in the power transmission system of provincial region r

443 in year t .

444 We use 1990 embodied GHG emission intensities and China's transmission infrastructure

445 data to estimate the cumulative emissions in 1990. We use this method to estimate the cumulative

446 emissions in 1990 considering that the scale of the transmission infrastructures before 1990 was

447 relatively small. For example, the length of 220 kV and above transmission lines in 1990 was only

448 13% of that in 2017. More importantly, the data on transmission line length and substation

449 installed capacity before 1990 are not available. Given this information, it should be noted that the

450 cumulative GHG emissions in 1990 may be underestimated because China's GHG emission

451 intensities before 1990 are higher than that of 1990.

452 **Scenario analysis.** A power transmission unit consisting of transmission lines and 2 substations or

453 converter stations can be considered the smallest power transmission system. A real power

454 transmission system comprises a certain number of units. Here, we conduct an analysis of GHG

455 emissions by a power transmission unit under different scenarios. In Scenario 1, the transmission

456 unit operates at the theoretical maximum transmission distance while in Scenario 2, the power

457 transmission unit operates at the actual transmission distance. The embodied GHG emissions per

458 kilometre of AC and DC power transmission units under voltage v (E_p^v) (Scenarios 1 and 2) can

459 be expressed as follows:

460
$$E_p^v = (\overline{E_{K,t}^v} \times L_{td}^v + 2 \times \overline{E_{C,t}^v}) / L_{td}^v \quad (13)$$

461 where L_{td}^v is the theoretical maximum transmission distance (Scenario 1) or the actual

462 transmission distance (Scenario 2) of the power transmission unit under voltage v . On this basis,

463 the embodied GHG emissions per kilometre and the capacity of AC and DC power transmission

464 units under voltage v (E_{PC}^v) (Scenario 3 and 4) can be obtained by

465
$$E_{PC}^v = E_p^v / TC^v \quad (14)$$

466 where TC^v is the theoretical maximum transmission capacity (Scenario 3) or the actual nominal

467 transmission capacity (Scenario 4) of the power transmission unit under voltage v .

468 **Uncertainty analysis**

469 The uncertainties of the GHG footprint in this study originate from three major sources,

470 specifically, the input inventories, GHG emission intensities and depreciation rate of the power

471 transmission infrastructure. Here, we adopted error propagation to estimate the overall

472 uncertainties⁴⁰. Specifically, stochastic modelling based on Monte Carlo simulation was used to

473 propagate the error in terms of the standard deviation (SD)^{41,42}. We define the order of magnitude

474 of each source data x as $\lg x$. Then, the absolute error of $\lg x$ can be approximated as:

475
$$d(\lg x) \approx \lg(x + dx) - \lg x = \lg\left(1 + \frac{dx}{x}\right) = \lg(1 + Rx) \quad (15)$$

476 where dx is the SD of x and Rx represents the relative SD (RSD) of x . Then, the perturbation of

477 x (denoted as x^p) satisfies the following equation:

478
$$\lg(x^p) \approx \lg x + d(\lg x) = \lg x + \lg(1 + Rx) \quad (16)$$

479 Thus, the Monte Carlo perturbation could be carried out for each data element to obtain the
480 perturbed GHG emission inventory E^P , intermediate matrix Z^P and final demand matrix Y^P . The
481 perturbed X^P can be obtained by summing Z^P and Y^P to maintain the balance of the IO table. A
482 3% threshold was set to exclude over-perturbation⁴³. It should be noted that the observations of
483 MRIO entries follow a lognormal distribution to avoid sign changes in Monte Carlo
484 perturbations⁴⁴. The perturbation was conducted for 10000 iterations, from which the overall SD
485 of the GHG footprint could be derived. For the cumulative GHG emissions, another influencing
486 factor is the depreciation rate of transmission lines and substations. We assume that the
487 depreciation rate follows a normal distribution. For further technical details and the RSDs of
488 different raw data, see Supplementary Method and Supplementary Tables 20–21.

489 **Data sources**

490 In this study, the MRIO database EXIOBASE was applied to calculate GHG emission
491 intensities^{45,46}. With 200 commodities and 163 industries, of which 33 represent the primary
492 sectors of the economy, EXIOBASE provides the highest consistent level of product and sector
493 detail by country among all currently available MRIO models⁴⁷, and we have matched the sectors
494 of EXIOBASE tables with the product/service input categories of this study (Supplementary Table
495 22). It should be noted that the study did not differentiate the GHG emission factors for each
496 provincial region in China, as the EXIOBASE MRIO tables are on the national scale.

497 China's power transmission system is dominated by overhead transmission line projects;
498 however, there are also a few exceptions. For example, the 500 kV cross-sea interconnection
499 project between Hainan and Guangdong crossing the Qiongzhou Strait uses submarine cable. The

500 input inventories of different overhead transmission lines and substation and converter station
501 projects⁴⁸ were derived from the State Grid Corporation of China (SGCC)⁴⁹. However, cable
502 transmission line projects were not considered by this study due to the lack of data. The data on
503 total transformer nameplate capacity, converter transformer capacity, and the total AC and DC
504 transmission line circuit lengths in each provincial region from 1990 to 2017 were derived from
505 the Annual Compilation of Statistics for Power Industry²⁵. However, because the statistics for 1992
506 were unavailable, this research used interpolation to estimate the missing data. The average
507 depreciation rate intervals of transmission lines and substations were collected from the NDRC²⁹.
508 The theoretical maximum transmission distance and transmission capacity of each voltage class
509 were those reported by Liu⁷.

510 **Data availability**

511 All the GHG emission inventories of power transmission projects and China's 31 provincial
512 regions' power transmission systems from 1990 to 2017 are listed in Supplementary Tables 5–18.

513 All our data are available to readers and can be freely downloaded from the CEADs website
514 (<https://www.ceads.net/data/process/>).

515

516 **Code availability**

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

519

520

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660

661 **Competing interests**

662 The authors declare no competing interests.

663

664 **Author contributions**

665 W.W., J.L., D.G., and N.Z. conceived the study. H.Q. and K.F. provided the data. W.W., J.L.,
666 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.,
667 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
668 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.,
669 N.Z., X.L., and J.X.) revised the manuscript.

670

671 **Figure Legends**

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

676

677 **Fig. 2 | Evolution of cumulative GHG emissions embodied in the power transmission**
678 **infrastructure of different provincial regions.** The cumulative embodied GHG emissions of different
679 provincial regions in (a) 1990 and (b) 2017. The cumulative embodied GHG emissions per unit area of

680 different provincial regions in (c) 1990 and (d) 2017. The cumulative embodied GHG emissions per
681 capita of different provincial regions in (e) 1990 and (f) 2017. (g) The Gini coefficient of embodied
682 GHG emissions per capita from 1990 to 2017.

683

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

695

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

705

706

707

708 **Tables**

709 **Table 1. Embodied GHG emissions of power transmission units under different**
 710 **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

711

712 ^a The embodied GHG emissions are based on typical transmission infrastructure projects in 2017.

713 ^b The theoretical maximum transmission distance and transmission capacity for each voltage class
 714 are derived from Liu⁷.

715 ^c The actual transmission distance and actual nominal transmission capacity for ±800 kV DC and
 716 1,000 kV AC systems are calculated using data from the National Energy Administration, State
 717 Grid Corporation of China and China Southern Power Grid Company Limited (Supplementary
 718 Tables 2-3).

719 ^d “-” represents no data.

720