

1 **Carbon emissions in China's thermal electricity and heating industry: An input-**
2 **output structural decomposition analysis**

3
4
5 **Abstract**

6 CO₂ emissions from China accounted for 27 per cent of global emissions in 2019. More
7 than one third of China's CO₂ emissions come from the thermal electricity and heating
8 sector. Unfortunately, this area has received limited academic attention. This research
9 aims to find the key drivers of CO₂ emissions in the thermal electricity and heating
10 sector, as well as investigating how energy policies affect those drivers. We use data
11 from 2007 to 2018 to decompose the drivers of CO₂ emissions into four types, namely:
12 energy structure; energy intensity; input-output structure; and the demand for electricity
13 and heating. We find that the demand for electricity and heating is the main driver of
14 the increase in CO₂ emissions, and energy intensity has a slight effect on increasing
15 carbon emissions. Improving the input-output structure can significantly help to reduce
16 CO₂ emissions, but optimising the energy structure only has a limited influence. This
17 study complements the existing literature and finds that the continuous upgrading of
18 power generation technology is less effective at reducing emissions and needs to be
19 accompanied by the market reform of thermal power prices. Second, this study extends
20 the research on CO₂ emissions and enriches the application of the IO-SDA method. In
21 terms of policy implications, we suggest that energy policies should be more flexible
22 and adaptive to the varying socio-economic conditions in different cities and provinces
23 in China. Accelerating the market-oriented reforms with regard to electricity pricing is
24 also important if the benefits of technology upgrading and innovation are to be realised.

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27 **Keywords**

28 Carbon dioxide reduction; Energy intensity; Energy structure; Electricity;
29 Decomposition analysis; China

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41 **1 Introduction**

42 Currently, China's electricity supply structure is primarily dominated by thermal
43 electricity, which accounts for more than 70 per cent of the total electricity generated
44 in the country; more than 60 percent of thermal electricity is generated by burning coal
45 (National Bureau of Statistics, 2016). In 2016, China's electric power industry
46 consumed 52 percent of the country's coal and released 34 per cent of the country's CO₂
47 emissions (Yang and Lin, 2016). The International Environment Agency (IEA) reported
48 that China's electric power industry released 48.6 per cent of the country's CO₂ in 2015,
49 which is higher than the global average of 41.9 per cent during the same period (IEA,
50 2016). In order to facilitate a move away from high carbon dependency, China has been
51 promoting a non-fossil energy substitution policy in order to transform the energy sector
52 and accelerate the upgrading of technology used within the industry.

53 During the 11th period (2006-2010) and the 12th period (2011-2015) of the five-
54 year plan¹, the Chinese government introduced a series of carbon reduction policies in
55 order to accelerate the upgrading of technology, reduce energy consumption and
56 optimise the energy structure in the thermal and heating sector. One of the key tasks
57 undertaken during the 12th period of the five-year plan was to advance the reforms in
58 energy production, prioritise and strengthen the energy conservation strategy, and
59 comprehensively improve the efficiency of energy conversion and utilisation (National
60 Energy Administration, 2013). However, despite these efforts, carbon emissions from
61 the thermal and heating sector continued to rise significantly during the period between
62 2007 and 2015 (National Energy Administration, 2016).

63 The contradiction between China's energy policy goals and the reality of the
64 situation has put great pressure on the country to achieve its carbon emission reduction
65 targets. In response to the huge pressures created by the low-carbon movement, the
66 National Development and Reform Commission (NDRC) held a press conference on
67 19th December 2017 at which they announced the official launch of the national carbon
68 emission trading system, and issued the 'national carbon emission trading market
69 construction plan (electricity generation industry)'. As the only industry to be included
70 in the early stages of creating the national carbon market, the electricity power industry
71 has formally entered the era of carbon constraints. In 2017, approximately 1,700
72 electrical enterprises were included in the national carbon market, emitting about 3
73 billion tons of carbon dioxide annually. However, due to the existing energy structure
74 and the historical electricity installation layout, it is likely that the domestic electricity
75 production structure will continue to be dominated by coal-fired plants. In other words,
76 it is difficult for China to effectively change its electricity supply structure, which
77 means that it will remain a predominantly high-carbon based system in the short term.
78 In addition to the current constraints on the electricity production structure, China's
79 electric power industry also has to contend with a significant carbon lock-in effect.
80 Through the use of measures such as the replacement of non-fossil energy, improving
81 the utilisation of coal, and upgrading the technology used to generate thermal electricity,

¹ The five-year plan is a blueprint that sets out goals and directions for the long-term development of China's national economy.

82 the industry succeeded in reducing carbon dioxide emissions by 13.7 billion tons from
83 2006 to 2018. However, the average operating lifespan of coal-fired generating units in
84 China is about 12 years, and the average operating lifespan of million-kilowatt units is
85 about 5 years; consequently, it is difficult to eliminate the carbon lock-in effect of
86 thermal electricity generation in the short term.

87 Previous studies have aimed to investigate the relative contributory factors to CO₂
88 emissions (Ang, 1999; Sun, 2005; Zhang et al., 2008, Mi, et al., 2017; Mi, et al., 2020;
89 Zheng et al., 2019). The most frequently used methods include the IPCC method (IPCC,
90 2006), the IPAT method (Fu et al., 2015), the metafrontier non-radial MCPPI method
91 (Zhou, 2012); the DEA method (Yang, 2009); and the LMDI method (Zhou, 2014; Liu,
92 2015). However, although these studies have examined various impact factors such as
93 the energy intensity and energy structure of energy-related CO₂ emissions, they have a
94 drawback in that they have mainly focused on a single CO₂ emissions index and failed
95 to comprehensively reflect the linkages between the different industrial sectors.
96 Therefore, it is hard to assess the impact of sectoral connection and economic structural
97 factors on carbon emissions.

98 To this end, this study is designed to explore two main perspectives: first, it
99 examines the energy structure, energy intensity, and electricity generation technology
100 on the production side; and second, it analyses electricity and heating demand on the
101 demand side. In order to identify the cause of the conflict between the objectives of
102 China's energy policy and the reality, it is important to quantify the drivers and assess
103 the impact of energy policy on each driver. Currently, CO₂ intensity and per capita CO₂
104 emissions are commonly used to assess CO₂ emissions (Fan et al., 2007; Jobert et al.,
105 2010). Based on the Input-Output (IO) tables that link the thermal electricity and
106 heating sector and other sectors, this study assesses the key factors that contribute to
107 generating CO₂ emissions, by examining the energy structure, energy intensity, and
108 electricity generation technology (Paul, 2016; Wang, 2010; Wang et al., 2019).

109 Although China is committed to optimising its energy structure and constantly
110 developing new thermal electricity generation technologies, carbon emissions from the
111 thermal electricity and heating sector have continued to rise. This study aims to examine
112 the key drivers of CO₂ emissions in the thermal electricity and heating sector, as well
113 as investigating how energy policies affect those drivers. In this study, we use an input-
114 output structural decomposition analysis (IO-SDA) method to investigate the drivers of
115 CO₂ emissions in China's thermal electricity and heating sector from 2007 to 2018. First,
116 we calculate the CO₂ emissions as well as assessing the energy structure. Second, the
117 study investigates the contribution and the evolutionary trend of the demand structure
118 of different industry sectors with regard to CO₂ emissions in China's thermal electricity
119 and heating sector. Third, the slack based measurement data envelopment analysis
120 (SBM-DEA) model with unexpected output, and the Adjacent Malmquist model, are
121 used to evaluate the energy efficiency and technical efficiency values for each of the
122 provinces, respectively. Finally, this study analyses the key drivers of CO₂ emission and
123 the internal causes of changes in each driver, as well as assessing the impact of energy
124 policy on each driver. The effect of optimising the energy structure of China's thermal
125 electricity and heating sector is also taken into consideration.

126 This research contributes to the existing literature regarding the reduction of CO₂
127 emissions from the electricity sector in the following ways. First, it complements the
128 relevant literature on the impacts of upgrading electricity generation technology on
129 reducing carbon emissions by introducing the Adjacent Malmquist model (Zhang, 2013;
130 Wang et al., 2019). The existing research argues that the continuous upgrading of
131 electricity generation technology has significantly reduced carbon emissions in China
132 (Zhang, 2013; Wang et al., 2019). Nevertheless, our study finds that the reality does not
133 conform to expectations of previous scholars, by capturing the actual situation
134 regarding emissions reduction in the thermal electricity and heating sector during the
135 period from 2007 to 2018, based on the three-yearly IO data. This finding helps to offer
136 insight into the potential conflict between energy policy and the reality of the situation
137 in practice. In addition, the dynamic analysis the of technical efficiency of the thermal
138 electricity and heating sector can help to predict further trends and enable energy policy
139 to be tailored accordingly.

140 Second, this study expands the literature on CO₂ emissions from electricity
141 generation in China (Zhang et al., 2013; Paul, 2016; Wang et al., 2019) by applying the
142 SBM-DEA model with unexpected output to assess the effects of energy structure
143 optimisation in the thermal electricity and heating sector for 30 provinces between
144 2007 and 2018. The existing research has only focused on the overall effect on
145 emissions reduction of optimising the energy structure, but without measuring the slack
146 and redundancy of the input and output variables. This aspect of the study complements
147 the existing related research, and provides a valuable reference that the government can
148 use to adjust the energy structure of the thermal electricity and heating sector in a
149 scientific and rational way, and to formulate appropriate energy structure optimisation
150 strategies.

151 Third, this study enriches the application of the IO-SDA method (e.g., Su and Ang,
152 2012; Su et al., 2013; Wei et al., 2017). By refining the decomposition, we clarify the
153 mechanism by which the industrial sectors' final demand is transmitted to the reduction
154 of emissions in the thermal electricity and heating sector. In addition, the impacts of
155 adjustments in energy consumption on the energy structure and the impact of energy
156 intensity on carbon emissions in different regions are also evaluated. The use of
157 provincial-level data and the refined analysis help to reveal differences between various
158 regions and thus provide a more detailed reference for formulating carbon emission
159 reduction policies. This part of the research also complements the Karmellos et al.'s
160 (2016) study by providing theoretical support for promoting the achievement of CO₂
161 reduction targets, specifically with regard to the thermal electricity and heating sector
162 in developing countries.

163 The paper is organised as follows: Section 2 reviews the literature in relation to
164 energy intensity, energy efficiency, electricity generation technology and energy
165 structure. Section 3 explains the data and methodology. Section 4 presents the results.
166 Section 5 offers a discussion and suggests policy implications. Section 6 summarises
167 the key findings of the paper and highlights the main contributions of this research.
168

169 **2 Literature review**

170 Carbon emissions from electricity generation dominate China's energy-related
171 CO₂ emissions. Evaluating the performance of fossil fuel electricity generation and its
172 potential for reducing carbon emissions are of great significance with regard to
173 promoting low-carbon development (Zhou, 2012). Many studies have explored
174 potential ways of reducing CO₂ emissions from electricity generation and provided
175 policy suggestions. For example, Maruyama and Eckelman (2009) estimated long-term
176 reduction trends in 138 countries and regions, with an emphasis on non-Organization
177 for Economic Cooperation and Development (OECD) countries, and Ang et al. (2011)
178 assessed CO₂ reduction in 129 countries, excluding the six Gulf Cooperation Council
179 member countries, recorded by the IEA statistical database. Unlike the benchmark
180 studies described above, Zhou (2012) applied a non-radial direction distance function
181 method to evaluate the effectiveness of CO₂ emission reduction strategies and found
182 that OECD countries performed better in terms of reducing CO₂ emissions from
183 electricity generation. There are two streams of literature related to our study. The first
184 stream focuses on evaluating the CO₂ index and exploring the energy intensity, energy
185 efficiency and electricity generation technology in China's electricity sector using the
186 framework of low carbon development. Studies within the second stream have tried to
187 identify the driving force(s) behind CO₂ emissions from the demand side.

188

189 *2.1 Energy intensity, energy efficiency and electricity generation technology*

190 *2.1.1 Energy intensity*

191 In terms of electricity generation, carbon intensity denotes the amount of carbon
192 emissions per unit of electricity generation (Peng and Tao, 2018). Zhang (2005)
193 investigated the carbon intensity of electricity generation in three Chinese provinces,
194 Guangdong, Liaoning and Hubei, from 1990 to 2010; he found that the declining trend
195 oincarbon intensity with regard to electricity generation and its provincial variations
196 were mainly due to complex central planning, financial and institutional factors. In order
197 to improve the estimation accuracy of carbon intensity in China's industrial sector
198 (including the electricity sector) and provide a more comprehensive reference for
199 energy policy, Liu (2015) firstly applied the Logarithmic Mean Divisia index (LMDI)
200 to conduct an in-depth study of the factors affecting carbon intensity and divided these
201 into three categories: the emission coefficient effect; the energy intensity effect; and the
202 energy structure effect. The results showed that the energy intensity effect was the main
203 driving force in terms of reducing carbon intensity from 1996 to 2012. Ang (2016)
204 studied the aggregate carbon intensity (ACI) for electricity generation at a national level
205 and found that the ACI in China had fallen from 0.905 in 1990 to 0.6916 in 2013. This
206 reduction could be due to improved energy efficiency rather than fuel switching.

207

208 *2.1.2 Energy efficiency*

209 With regard to electricity generation, many studies have applied the production
210 efficiency approach, involving methods such as data envelopment analysis (DEA), to

211 investigate the efficiency of thermal electricity generation in China. Yang (2009)
212 established six models based on DEA to assess the performance of each decision unit.
213 Yang (2010) evaluated the energy efficiency of China's thermal electricity production
214 in 2002. In addition, Zhou et al. (2012) also used the DEA model to explore the
215 efficiency of thermal electricity generation. As well as conducting DEA, Zhou (2014)
216 used the LMDI method to investigate the efficiency of China's thermal electricity
217 generation on a regional basis from 2004 to 2010. He found that reducing energy
218 intensity and optimising the energy structure can contribute to CO₂ reduction. Liu (2015)
219 applied the LMDI to decompose China's carbon intensity into three different effects:
220 the emission coefficient effect; the energy intensity effect; and the energy structure
221 effect for the period from 1996 to 2012; he found that energy efficiency improvement
222 plays a key role in reducing energy intensity. In addition to this, Choi and Ang (2012)
223 applied an attribution analysis to quantify the real changes that had occurred in terms
224 of energy intensity. They concluded that the effects of energy intensity mainly
225 contribute to reducing carbon intensity and also found that the effect of the emission
226 coefficient on carbon intensity increased with the expansion of electricity consumption.
227

228 *2.1.3 Electricity generation technology and energy structure*

229 To provide insights into the effects of technological innovation and structural
230 adjustment that have occurred within China's electricity industry in recent years, Peng
231 and Tao (2018) investigated changes in the carbon intensity of electricity from 1980 to
232 2014. They found that, since 1980, the impact of technological innovation on the
233 decline in carbon intensity has been greater than that of structural adjustment. However,
234 as electricity generation technology matures, carbon emission reduction in China's
235 electricity industry will come to rely mainly on renewable energy. Researchers have
236 devoted much attention to evaluating the work of decision-making units. Many existing
237 studies attribute the inefficiency in the electricity industry to the ineffective
238 management of decision-making units, as well as the fact that the generally
239 unfavourable operating environment has been neglected. In a departure from other
240 studies, Yang (2009) applied the DEA approach to studying coal-fired electricity plants
241 in China and found that the unfavourable operating environments in some electricity
242 plants resulted in relatively low-efficiency scores. The implementation of appropriate
243 market and regulatory mechanisms could eliminate this inefficiency and bring
244 substantial economic and environmental benefits. In order to identify the dynamic
245 changes in total-factor carbon emission performance that have taken place, Zhang (2013)
246 proposed using the metafrontier non-radial Malmquist CO₂ emission performance
247 index (MCPI) method to estimate these changes in China's thermal electricity plants
248 from 2005 to 2010. The study found that technological advances and changes in energy
249 structure can have a positive influence on reducing CO₂ emissions.

250 Even though many studies have employed the decomposition method to
251 investigate energy-related emissions, less attention has been paid to the linkages
252 between energy policy and the various drivers. In this study, we apply the IO-SDA
253 method to analyse the factors driving CO₂ emissions in the thermal electricity and
254 heating sector and investigate the historical evolution of each of the drivers that

255 accompanied the implementation of the energy policies. This leads us to a different
256 conclusion from that which has been reached by the existing studies. Related literature
257 has mainly focused on the factors driving carbon emissions from coal-fired electricity
258 plants before 2012. Our research spans a time period covering three five-year plans,
259 which allows us to explore the contradiction between the policy objectives and
260 outcomes. This helps us to explore the causes of this and ascertain what influenced the
261 policy outcomes and the possible deviations from the policy.

262 Second, some of the related research has applied the DEA model to explore the
263 efficiency of thermal electricity generation to assess its impact on CO₂ emissions. In
264 this study, we introduce the SBM-DEA model and treat CO₂ emissions as an unexpected
265 output in order to assess the energy efficiency of the thermal electricity and heating
266 sector for 30 provinces from 2007 to 2018. By measuring the slack and redundancy of
267 the input and output variables, this study proposes a scheme to optimise the energy
268 structure of the thermal electricity and heating sector, which provides a valuable
269 reference that the government can use to formulate energy structure optimisation
270 strategies in a scientific way. In addition, this study further measures the dynamic
271 technical efficiency within the thermal electricity and heating sector by applying the
272 Adjacent Malmquist model, which is conducive to predicting future trends and
273 formulating appropriate energy policies. Third, most studies have mainly focused on a
274 single CO₂ emissions index and failed to comprehensively reflect the linkages between
275 the different industrial sectors. Therefore, it is hard to assess the impact of sectoral
276 connection and economic structural factors on carbon emissions. This paper further
277 investigates the impact of technological progress, the energy consumption structure and
278 economic scale among different industrial sectors on CO₂ emissions.

279

280 *2.2 Electricity demand*

281 Demand for electricity has been rising steeply in China during recent years.
282 Increasing fluctuations in electricity demand and insufficient peak shaving (levelling
283 out of peaks in electricity demand) capacity within the electricity supply system
284 constitute two major problems. Analysing changes in demand for electricity within
285 different industrial sectors can provide a reference for electricity demand forecasting,
286 as well as useful guidance for formulating industrial electricity saving and electricity
287 development plans and/or policies. In order to predict China's electricity demand and
288 ensure a stable electricity supply, Paul (2016) applied a decomposition analysis method
289 to assess the effect of changes in various industrial sectors on electricity demand from
290 1998 to 2002. During the period from 1998 to 2007, China's industrial electricity
291 consumption increased dramatically. In response to this, Wang (2010) applied the
292 LMDI approach to assess the driving forces behind this growing demand for electricity,
293 and found that the production of electricity and heat was one of the biggest contributors.
294 They concluded that these sectors should be given priority in terms of industrial
295 restructuring. Wang et al. (2019) applied a modified SDA model to assess the key
296 factors accounting for the rise in CO₂ emissions from electricity generation in China
297 between 2007 and 2012. He found that the increase in CO₂ emissions resulting from
298 electricity generation was mainly driven by changes in electricity demand.

299 Some existing studies have investigated the effect of changes in the industrial
300 sector on electricity demand by applying the decomposition analysis method, such as
301 those by Paul (2016) and Wang et al. (2019), described above. However, the demand
302 for electricity from China's industrial sector increased rapidly from 2007 to 2015,
303 accounting for approximately 72 per cent of China's total electricity consumption
304 (National Energy Administration, 2016). It is debatable whether the effects of the
305 demand from the industrial sector for electricity are currently still following the same
306 trajectory outlined by Paul (2016) and Wang (2019), as it may be that some structural
307 adjustment to demand has occurred within the industrial sector. Thus, it is important to
308 study the factors that contribute to demand for electricity and to decompose the drivers
309 of carbon emissions resulting from electricity generation. In addition, this study
310 explores how the consumption trends of various industrial sectors evolved during the
311 period from 2007 to 2015 in order to discover which sectors had a high demand for
312 electricity and heating. These results will help to provide policy suggestions to
313 accelerate the optimisation of the demand structure on the consumption side and
314 achieve the short-term goal of reducing emissions.

315

316 **3 Data and methodology**

317 *3.1 Data sources*

318 The data used for this study are derived from China's Energy Balance tables, and
319 the China Energy Statistical Yearbook and Input-Output (I-O) tables for 2008, 2011,
320 2013, 2016 and 2019 (The yearbook releases data with a one-year lag, which means the
321 2008 statistical yearbook contains data for 2007, and so on). The data consists of input
322 and output data for 42 industrial sectors, 20 types of energy input data for the thermal
323 power and heating departments of 30 provinces, and output data on power, heat and
324 CO₂. China is divided into four economic regions, namely the eastern, central, western
325 and northeastern regions. Due to the availability of data, we only studied 30 provinces,
326 which are divided as follows: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang,
327 Fujian, Shandong, Guangdong and Hainan belong to the eastern region; Shanxi, Anhui,
328 Jiangxi, Henan, Hubei and Hunan are located in the central region; Inner Mongolia,
329 Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia
330 and Xinjiang belong to the western region; and Liaoning, Jilin and Heilongjiang form
331 part of the northeastern region. We adjusted the I-O tables according to the constant
332 price in 2007 and subtracted the imports, because these are produced abroad and
333 therefore do not consume any of China's products and energy in the manufacturing
334 process. The energy balance sheet provides the figures for the usage of each energy
335 source. The conversion standard refers to the conversion coefficient published by the
336 National Bureau of Energy Statistics. The carbon emission coefficients and the average
337 lower heating value of each energy source refers to data published in the 2006
338 Intergovernmental Panel on Climate Change (IPCC) report. The I-O table gives
339 statistics for the intermediate input, final use, and total output data of each sector. We
340 used the year 2007 as the base period and adjusted the corresponding I-O tables using
341 the constant price in 2010, 2012, 2015 and 2018, respectively. The amount of energy

342 used in thermal electricity generation and the heating sector, for each category of energy,
 343 is shown in Table 1. We applied the SBM-DEA model to study the optimisation of the
 344 energy structure, and because the model has quantitative requirements regarding the
 345 input variables, output variables and the number of decision making units, we combined
 346 the 20 input energy sources into 4 types: namely, Total Coal; Total Petroleum Products;
 347 Coal Gas; and Gas (the quantity selection criteria used for the variables are explained
 348 in subsection 3.2.2).

349

350 **Table 1**

351 Energy use (unit: 10^4 tce) in thermal electricity generation and heating sector.

Classification of energy	Categories of energy	2007	2010	2012	2015	2018
Total Coal	Raw Coal	101609.9	118482.8	139522.5	142869.8	165963.2
	Cleaned Coal	40.47	13.7	90.95	79.07	0
	Other Washed Coal	1301.99	1395.08	1197.24	1182.43	1871.2
	Briquettes	0	0	0	0	0
	Coke	0	0	0	273.89	20.65
	Other Coking Products	0	0	0	0	0
Total Petroleum Products	Crude Oil	23.59	9.99	17.46	27.36	21.86
	Gasoline	0.19	0.13	0.12	0.35	0.1
	Kerosene	0	0	0	0	0
	Diesel Oil	337.19	171.44	55.38	41.64	45.96
	Fuel Oil	995.83	464.62	329.19	280.93	106.67
	Refinery Gas	256.52	392.52	324.97	286.2	363.12
	Other Petroleum Products	240.74	151.91	29.3	50.34	21.38
Gas	Liquefied Natural Gas (LNG)	8.79	1.51	0.12	5.61	6.87
	Natural Gas	1226.22	2314.83	2897.87	4310.14	6388.16
	Liquefied Petroleum Gas (LPG)	0	310.09	329.69	303.93	364.72
Coal Gas	Coke Oven Gas	5476.95	10573.78	12214.61	13667.46	13638.41
	Blast Furnace Gas	0	14818.96	18469.02	26825.7	37130.04

Converter Gas	0	1793.37	3394.02	3631.54	7294.4
Other Gas	11661	0	0	228.39	86.25

352 Data source: China Energy Statistics Yearbook 2008–2019. The yearbook releases data with a one-year
353 lag.

354

355 The conversion factors for calculating CO₂ emission from different types of energy
356 are shown in Table 2.

357

358 **Table 2**

359 Conversion factors for calculating CO₂ emissions from different types of energy.

Categories of energy	CO ₂ emissions per heat unit (t /10 ³ J)	Average lower calorific value (10 ⁻⁶ J/t)	CO ₂ emission factors (t CO ₂ /t)	Conversion coefficient to standard coal (t tec/t)
Raw Coal	97967	20908	2.4083	0.7143
Cleaned Coal	97967	26344	2.5808	0.9
Other Washed Coal	97967	8363	0.8193	0.357
Briquettes	97500	8363	0.8154	0.6
Coke	107000	28435	3.0425	0.9714
Coke Oven Gas	44400	16726(10 ³ J/m ³)	7.4263(10 ⁻⁴ t/m ³)	5.93
Blast Furnace Gas	260000	5227(10 ³ J/m ³)	13.5902(10 ⁻⁴ t/m ³)	1.286
Converter Gas	260000	5227(10 ³ J/m ³)	13.5902(10 ⁻⁴ t/m ³)	2.286
Other Gas	260000	5227(10 ³ J/m ³)	13.5902(10 ⁻⁴ t/m ³)	6.9
Other Coking Products	97500	33453	3.2617	1.3
Crude Oil	73300	41816	3.0651	1.4286
Gasoline	70000	43070	3.0149	1.4714
Kerosene	71900	43070	3.0967	1.4714
Diesel Oil	74100	42652	3.1605	1.4571
Fuel Oil	77400	41816	3.2366	1.4286
LPG	63100	50179	3.1663	1.7143
Refinery Gas	57600	46055	2.6528	1.5714
Other Petroleum Products	73300	41816	3.0651	1.2
Natural Gas	56100	38931(10 ³ J/m ³)	21.8403(10 ⁻⁴ t/m ³)	1.22
LNG	56100	54071	3.0334	1.7572

360 Note: The LNG data was computed using the mass and volume.

361

362 The data source, China's Energy Balance Sheet, listed 17 different energy sources
363 for 2007 and 20 energy sources for 2012 and 2015. In order to standardise them, we
364 classified the energy sources into 17 categories. Given the data availability, this study

365 followed the classification used by Wang et al. (2019) and merged the original 42
 366 sectors in the I-O table into 9 sectors. Table 3 shows the descriptive statistics for various
 367 data.

368

369 **Table 3**

370 Descriptive statistics.

	Year	n	Min	Max	Mean	SD
Total Coal (unit: 10 ⁴ tce)	2007-2018	150	104.55	20025.72	4749.00	4003.80
Total Petroleum Products (unit: 10 ⁴ tce)	2007-2018	150	0.00	818.35	32.33	77.91
Gas (unit: 10 ⁴ tce)	2007-2018	150	0.00	1634.00	128.60	259.68
Coal Gas (unit: 10 ⁴ tce)	2007-2018	150	0.00	19029.56	1877.33	2650.88
Heat (10 ¹⁰ kJ)	2007-2018	150	47.90	133092.95	17569.61	19984.39
Power (10 ⁸ kW•h)	2007-2018	150	83.10	5488.24	1302.24	1083.79
CO ₂ (unit: 10 ⁴ tons)	2007-2018	150	779.07	108924.47	25994.67	21832.96

371

372 3.2 The Model

373 The decomposition of factors driving CO₂ emissions in the thermal electricity and
 374 heating sector from 2007 to 2018 and the analysis of the internal causes are depicted in
 375 Fig. 1. The research flow chart is divided into four steps.

376 First, we collected relevant data from 30 provinces and 42 industrial sectors for
 377 the period 2007-2018. This consisted of the annual consumption figures for 20 types of
 378 energy use, heat, power generation and CO₂ emissions from thermal power and heating
 379 sector for 30 Chinese provinces, and the I-O data for all 42 industrial sectors from the
 380 I-O tables. For modelling purposes, the different types of energy use are regarded as the
 381 inputs, while heat, power generation and CO₂ emissions are regarded as the three
 382 outputs, of which CO₂ emissions are treated as the undesirable output.

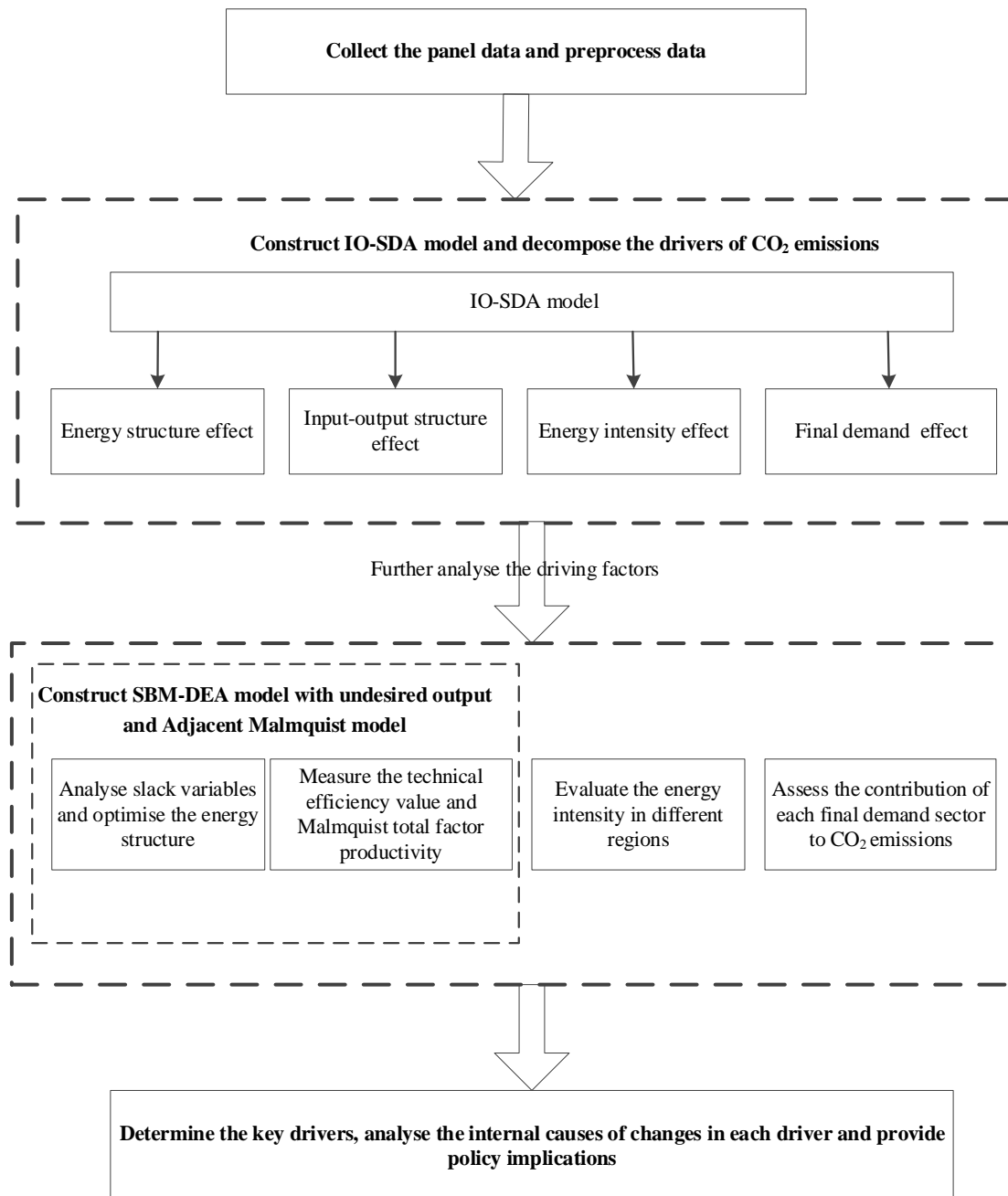
383 Second, the IO-SDA model was introduced to decompose the factors driving CO₂
 384 emissions into four types, namely: energy structure; energy intensity; input-output
 385 structure; and the demand for electricity and heating. Subsequently, the contribution of
 386 each driver to the thermal electricity and heating sector, and its evolutionary trend, were
 387 examined.

388 Third, the SBM-DEA model and Adjacent Malmquist model were constructed to
 389 evaluate the energy efficiency (to help us assess how the energy structure can be
 390 optimised) and technical value (to help us assess the effect of the input-output structure)
 391 for each of the provinces, respectively. The slack variables of various provinces, and
 392 the possible reasons behind the adynamic change in energy efficiency and technical
 393 value were then analysed. Based on the analysis of the slack variables, this study
 394 provides energy structure optimisation schemes for the thermal electricity and heating
 395 sector. In addition, changes in CO₂ emissions resulting from technological upgrading

396 were also measured using the Adjacent Malmquist model. The study then evaluated the
 397 energy intensity in different regions to assess the contribution of the final demand in
 398 each sector to CO₂ emissions in order to further analyse the energy intensity effect and
 399 the final demand effect.

400 Finally, this study uncovered the key drivers of CO₂ emissions, as well as
 401 analysing the internal causes of changes in each driver and assessing the impact of
 402 energy policy on each driver. Some suggestions for optimising the energy structure,
 403 improving the energy intensity, increasing technical emissions reduction, and policy
 404 implications are then provided based on the experimental results.

405



406

407

408

Fig. 1. Flow chart of the research process

409 3.2.1 I-O SDA model

410 The I-O tables reveal the complex interdependencies between different economic
 411 sectors, as well as showing how commodity production and commodity exchange are
 412 linked. I-O tables are therefore widely used to measure direct and indirect CO₂
 413 emissions in various sectors. For the I-O table, the direct consumption coefficient
 414 matrix A can be set as:

$$415 \quad A = [a_{ij}], a_{ij} = \frac{Z_{ij}}{Z_j} \quad (1)$$

416 where Z_{ij} refers to the intermediate input from sector i to sector j , $i=1,2,\dots,n$,
 417 $j=1,2,\dots,n$. $Z = [z_i]$ represents the total output of sector i . $Y = [y_i]$ denotes the final
 418 demand from sector i . The total output vector can then be expressed as:

$$419 \quad \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{pmatrix} + \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \quad (2)$$

420 Formula (2) can be transformed into:

$$421 \quad AZ + Y = Z \quad (3)$$

422 Then, equation (3) can be simplified as:

$$423 \quad Z = (I - A)^{-1} Y \quad (4)$$

424 where I represents the identity matrix and $L = (I - A)^{-1}$ represents Leontief's inverse
 425 matrix. In sector i , the CO₂ generated by consuming the energy source k can be
 426 calculated as:

$$427 \quad E_{ik} = f_k \times C_{ik} = \frac{E_{ik}}{C_{ik}} \times C_{ik}, i=1,2,\dots,n, k=1,2,\dots,m. \quad (5)$$

428 where f_k denotes the CO₂ emission coefficient of energy source k and C_{ik}
 429 represents the amount of energy combustion of energy source k , $k=1,2,\dots,m$.

430 The CO₂ emission coefficient of energy source k is computed as follows:

$$431 \quad f_k = T_k \times Q_k \quad (6)$$

432 where T_k is the amount of CO₂ emissions per unit of heat produced by

433 combusting the energy source k ; Q_k is the average lower heating value of energy
 434 source k . The values of T_k and Q_k were obtained from the IPCC (2006). In order to
 435 explore the impacts of the energy structure, energy intensity, the input-output structure
 436 and final demand on CO₂ emissions, we transformed C_{ik} from formula (5) into

437 $C_{ik} = \frac{C_{ik}}{C_i} \times \frac{C_i}{X_i} \times X_i$ and obtained the following:

$$438 \quad E_{ik} = \frac{E_{ik}}{C_{ik}} \times \frac{C_{ik}}{C_i} \times \frac{C_i}{Z_i} \times (I - A)^{-1} Y_i, i = 1, 2, \dots, n, k = 1, 2, \dots, m \quad (7)$$

439 where $F = \frac{E_{ik}}{C_{ik}}$ denotes the CO₂ emission coefficient matrix and $F_{n \times m} = (f_1 \ f_2 \ \dots \ f_m)$.

440 $S_{m \times n} = [s_{ik}]$, $s_{ik} = \frac{C_{ik}}{C_i}$ represents the energy consumption structure matrix. $I_{n \times n} = \frac{C_i}{Z_i}$ is

441 the energy intensity matrix. $L_{n \times n} = (I - A)^{-1}$ represents the effect of the input-output
 442 structure on total CO₂ emissions, which reflects the contribution of technological
 443 improvements to CO₂ emissions in the production process. $Y = (y_1, y_2, \dots, y_n)^{-1}$ denotes
 444 the final demand matrix, reflecting the impact of the demand for the final product on
 445 total CO₂ emissions.

446 The energy consumption structure matrix S and the energy consumption intensity
 447 matrix I can be expressed as:

$$448 \quad S_{m \times n} = \begin{pmatrix} \frac{C_{11}}{\sum_{k=1}^m C_{1k}} & \frac{C_{12}}{\sum_{k=1}^m C_{1k}} & \dots & \frac{C_{1n}}{\sum_{k=1}^m C_{1k}} \\ \frac{C_{21}}{\sum_{k=1}^m C_{2k}} & \frac{C_{22}}{\sum_{k=1}^m C_{2k}} & \dots & \frac{C_{2n}}{\sum_{k=1}^m C_{2k}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{C_{m1}}{\sum_{k=1}^m C_{ik}} & \frac{C_{m2}}{\sum_{k=1}^m C_{ik}} & \dots & \frac{C_{mn}}{\sum_{k=1}^m C_{ik}} \end{pmatrix}, \quad I_{n \times n} = \begin{pmatrix} \frac{\sum_{k=1}^m C_{1k}}{X_1} & 0 & \dots & 0 \\ 0 & \frac{\sum_{k=1}^m C_{2k}}{X_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \frac{\sum_{k=1}^m C_{nk}}{X_n} \end{pmatrix} \quad (8)$$

449 where C_{ik} denotes sector i 's demand for energy source k .

450 By calculating the sum of the CO₂ emissions produced from the m energy
 451 sources consumed by sector i , we can obtain the total amount of CO₂ emitted by sector
 452 i :

453
$$E_i = \sum_{k=1}^m E_{ik} \quad (9)$$

454 The total amount of CO₂ emissions from the thermal and heating sector can then
 455 be established by combining equation (7) and equation (9):

456
$$E_h = \sum_{k=1}^m \frac{E_{hk}}{C_{hk}} \times \frac{C_{hk}}{C_h} \times \frac{C_h}{X_h} \times (I-A)^{-1} Y_h = FSILY \quad (10)$$

457 According to equation (10), the changes in CO₂ emissions from the thermal
 458 electricity and heating sector in two adjacent periods ΔE_h can be expressed as follows:

459
$$\Delta E_h = F_t S_t I_t L_t Y_t - F_{t-1} S_{t-1} I_{t-1} L_{t-1} Y_{t-1} \quad (11)$$

460 The SDA method can involve many different forms of decomposition. In order to
 461 reduce the errors, this study uses bipolar decomposition to decompose the total amount
 462 of CO₂ emitted by the thermoelectric and heating sector. More detail about the SDA
 463 decomposition method can be found in the following references: Dietzenbacher and
 464 Los (1998); Haan (2001); Hoekstra and Bergh (2002); Liang et al. (2013); and Rørmoose
 465 and Olsen (2005).

466
$$\begin{aligned} \Delta E_h = & \underbrace{\frac{(F_t + F_{t-1})(I_t + I_{t-1})(L_t + L_{t-1})(Y_t + Y_{t-1})}{2^4} \Delta S}_{\text{energy structure effect}} \\ & + \underbrace{\frac{(F_t + F_{t-1})(S_t + S_{t-1})(L_t + L_{t-1})(Y_t + Y_{t-1})}{2^4} \Delta I}_{\text{energy intensity effect}} \\ & + \underbrace{\frac{(F_t + F_{t-1})(S_t + S_{t-1})(I_t + I_{t-1})(Y_t + Y_{t-1})}{2^4} \Delta L}_{\text{input-output structure effect}} \\ & + \underbrace{\frac{(F_t + F_{t-1})(S_t + S_{t-1})(I_t + I_{t-1})(L_t + L_{t-1})}{2^4} \Delta Y}_{\text{final demand effect}} \end{aligned} \quad (12)$$

467 The formula for calculating changes in the total amount of CO₂ emissions
 468 produced by the thermal electricity and heating sector can be rewritten as follows:

469
$$\Delta E_h = \Delta E_S + \Delta E_I + \Delta E_L + \Delta E_Y \quad (13)$$

470 where $\Delta E_S = \frac{(F_t + F_{t-1})(I_t + I_{t-1})(L_t + L_{t-1})(Y_t + Y_{t-1})}{2^4} \Delta S$, $\Delta E_I = \frac{(F_t + F_{t-1})(S_t + S_{t-1})(L_t + L_{t-1})(Y_t + Y_{t-1})}{2^4} \Delta I$

471 $\Delta E_L = \frac{(F_t + F_{t-1})(S_t + S_{t-1})(I_t + I_{t-1})(Y_t + Y_{t-1})}{2^4} \Delta L$, $\Delta E_Y = \frac{(F_t + F_{t-1})(S_t + S_{t-1})(I_t + I_{t-1})(L_t + L_{t-1})}{2^4} \Delta Y$

472 ΔE_S denotes the changes in total CO₂ emissions caused by changes in energy structure.

473 ΔE_I represents the changes in total CO₂ emissions due to changes in energy intensity.

474 ΔE_L represents the changes in total CO₂ emissions caused by changes in the

475 intermediate input-output structure. Lastly, ΔE_Y denotes the changes in total CO₂

476 emissions caused by changes in the final demand. In order to further evaluate the impact

477 of energy structure adjustment and changes in final demand on CO₂ emissions reduction,

478 we decomposed the energy structure effect and final demand effect, as follows:

$$479 \quad SE_k = \frac{(F_t + F_{t-1})\Delta S_k(I_t + I_{t-1})(L_t + L_{t-1})(Y_t + Y_{t-1})}{2^4} \quad (14)$$

$$480 \quad FDE_i = \frac{(F_t + F_{t-1})(S_t + S_{t-1})(I_t + I_{t-1})(L_t + L_{t-1})}{2^4} \Delta Y_i \quad (15)$$

481 where ΔS_k represents the changes in the consumption of energy source k

482 between two periods, and ΔY_i denotes the output changes in sector j between two

483 periods. SE_k is the contribution made to reducing emissions by each energy source in

484 terms of the energy structure effect and $\sum_{k=1}^m SE_k = \Delta E_S$. FDE_j represents the impact

485 of changes in the demand scale of industry i on the final demand. $\sum_{i=1}^n FDE_i = \Delta E_Y$

486 denotes the final demand effect.

487 3.2.2 SBM-DEA model with undesirable output

488 In order to further evaluate the energy structure optimisation approach and

489 measure the energy efficiency of the thermal electricity and heating sector, the SBM-

490 DEA model was innovatively applied to estimate the slack variables and technical

491 efficiency. DEA is suitable for dealing with production activities with multi-inputs and

492 multi-outputs of Decision Making Units (DMU), and has been widely used to evaluate

493 the relative efficiency of DMU (Cong et al., 2021; Zhang et al., 2021). The principle

494 that DEA works on is to determine the relatively effective frontier of DMU by using

495 linear programming and convex analysis methods on the basis of keeping the input or

496 output unchanged, and then projecting each DMU onto the production frontier. The

497 relatively effective frontier of DMU represents the top surface of a convex polyhedron

498 which composed of productive effective points in all DUMs. Efficient point falls on the

499 frontier and its efficiency value is 1; invalid points are surrounded by the frontier, and

500 the efficiency value is between 0 and 1. The relative effectiveness of DMU was

501 evaluated by comparing the degree of deviation from the DEA frontier.

502 However, traditionally DEA uses either the radial or angular measurement method.

503 The radial method often ignores the slack problem and thus the efficiency value of the
 504 production unit may be overestimated (Han et al., 2020; Cong et al., 2021). The angular
 505 method tends to bias the efficiency measurement results of the production units. In order
 506 to avoid any measurement errors caused by the shortcomings of the aforementioned
 507 two methods, Tone (2001) proposed a non-angular and non-radial SBM model. Both
 508 the SBM and CCR model are based on the constant return to scale principle. Unlike
 509 traditional DEA, the SBM-DEA can evaluate the efficiency values from both the input
 510 and output perspectives (Sun and Huang, 2021).

511 Based on Tone's (2001) method, we assumed that there are k DMUs. Each DMU
 512 has m input factors and n output factors, $X = (x_{ij}) \in \mathbf{R}^{m \times k}$ denotes the input matrix
 513 and $Y = (y_{ij}) \in \mathbf{R}^{n \times k}$ represents the output matrix. The possible production set can be
 514 defined as $P = \{(x, y) | x \geq X\lambda, y \leq Y\lambda, \lambda \geq \mathbf{0}\}$, where λ is the non-negative weight
 515 vector on the real set \mathbf{R}^k , $X\lambda$ and $Y\lambda$ denotes the input and output values on the
 516 frontier. For a particular $DMU_0(x_0, y_0)$, the efficiency value of $DMU_0(x_0, y_0)$ can
 517 be evaluated by using the following SBM-DEA model:

$$518 \quad \rho^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{n} \sum_{r=1}^n \frac{s_r^+}{y_{r0}}} \quad (16)$$

$$s.t. \begin{cases} \mathbf{x}_0 = X\lambda + \mathbf{s}^- \\ \mathbf{y}_0 = Y\lambda - \mathbf{s}^+ \\ \lambda, \mathbf{s}^-, \mathbf{s}^+ \geq \mathbf{0} \end{cases}$$

519 where ρ^* denotes the efficiency value of $DMU_0(x_0, y_0)$ and $\sum \lambda = 1$. $\mathbf{s}^- \in \mathbf{R}^m$
 520 represents the slack variable for m desirable inputs, and s_i^- denotes the redundancy of
 521 the i th input. $\mathbf{s}^+ \in \mathbf{R}^n$ represents the slack variable for n outputs, and s_r^+ denotes the
 522 deficiency of the r th output.

523 Thermal power plants produce not only desired electricity and heat, but also
 524 undesired outputs such as CO_2 . In order to measure the energy efficiency and technical
 525 efficiency more accurately, the undesirable outputs are taken into consideration. Based
 526 on the above model, the updated SBM-DEA model with undesirable outputs can be
 527 shown as follows:

$$\min \rho = \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{n_1 + n_2} \left(\sum_{r=1}^{n_1} \frac{s_r^{e+}}{y_{r0}^e} + \sum_{j=1}^{n_2} \frac{s_j^{u+}}{y_{j0}^u} \right)}$$

$$s.t. \begin{cases} \mathbf{x}_0 = X \boldsymbol{\lambda} + \mathbf{s}^- \\ \mathbf{y}_0^e = Y^e \boldsymbol{\lambda} - \mathbf{s}^{e+} \\ \mathbf{y}_0^u = Y^u \boldsymbol{\lambda} + \mathbf{s}^{u+} \\ \boldsymbol{\lambda}, \mathbf{s}^-, \mathbf{s}^{e+}, \mathbf{s}^{u+} \geq 0 \end{cases} \quad (17)$$

528

529 where $\rho, \mathbf{s}^-, \mathbf{s}^{e+}, \mathbf{s}^{u+}$ represents the efficiency value, input redundancy, desirable

530 output deficiency and undesirable output redundancy, respectively. $DMU_0(x_0, y_0)$ is

531 valid only when ρ is equal to 1. At this point, $\mathbf{s}^- = 0, \mathbf{s}^{e+} = 0$ and $\mathbf{s}^{u+} = 0$. If $\rho < 1$, the

532 $DMU_0(x_0, y_0)$ is invalid and the input and output need to be further optimised.

533 Although the non-parametric analysis method requires a smaller quantity of DMU
534 than the parametric method, if the number of DMU is less than that of the input-output
535 index ($k < m + n$), the results are likely to indicate that most or even all the DMUs are
536 effective, and thus the model's evaluative ability will be compromised. Generally
537 speaking, the number of DMU should not be less than the product of the number of
538 input and output indicators, and not less than 3 times the number of input and output
539 indicators (Cooper et al., 2007) (see formula (18)). In terms of the model's practical
540 application, the data availability and DEA analysis results should be taken into
541 consideration when deciding how many DMUs to select. If the model has insufficient
542 ability to differentiate, the input or output indicators should be reduced according to the
543 actual situation to improve the degree of differentiation.

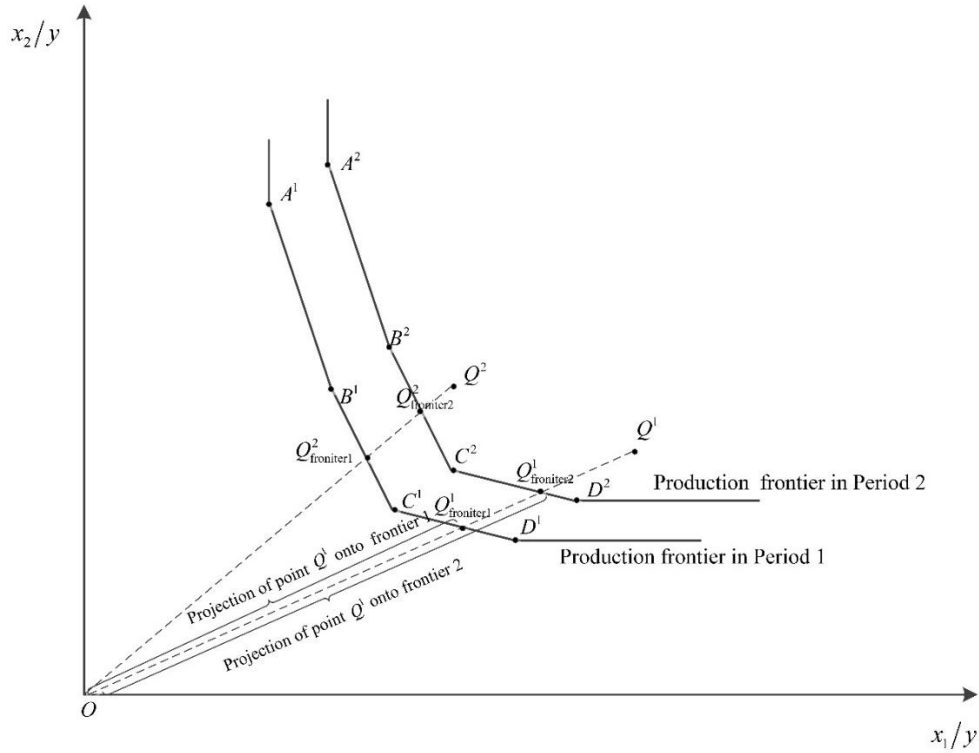
$$544 \quad k \geq \max \{m \times n, 3 \times (m + n)\} \quad (18)$$

545 3.2.3 Adjacent Malmquist model

546 Since Tone (2001) proposed an improved SBM model which included an
547 undesirable output, this model has been widely applied in the evaluation of economic
548 development efficiency and energy efficiency, etc., for example: sustainability
549 efficiency evaluation (Jiang et al., 2021), and energy efficiency (Rao et al., 2012),
550 energy structure optimisation (Sun and Huang, 2021), energy supply efficiency (Cong
551 et al., 2021). Traditional DEA models, such as the Constant Return to Scale (CRS)
552 model, Variable Return to Scale (VRS) model, and SBM model, only evaluate the
553 technical efficiency at a specific time based on sectional data.

554 However, technical efficiency is a long-term process which changes continually
555 over time. When the evaluated DMU data is panel data that includes multiple points in

556 time, the results obtained using the traditional DEA evaluation method would be
 557 unrealistic, because they are likely to ignore the time effect and the changes in the
 558 common frontier. In order to solve the problems associated with analysing panel data
 559 and evaluate the dynamic changes in productivity, the Malmquist total factor
 560 productivity index analysis method can be used. In our study, the Adjacent Malmquist
 561 model is introduced to calculate the dynamic technical value for the thermal electricity
 562 and heating sector from 2007 to 2018. To demonstrate the principle behind the
 563 Malmquist total factor productivity index, we take the input-oriented CRS model as an
 564 example (see Fig. 2).



565

Fig. 2 Malmquist productivity index diagram (input-oriented CRS)

566

567 We assumed that subscript 1 and subscript 2 represent the data for Q in period 1
 568 and period 2, respectively. The frontier of period 1 is composed of $A^1B^1C^1D^1$, and the
 569 frontier of period 2 is composed of $A^2B^2C^2D^2$. For a particular $DMU_0(x_0, y_0)$, the
 570 productivity changes in the two periods depend on and vary with the production frontier.
 571 Taking production frontier 1 as the benchmark, the Malmquist productivity index of Q
 572 is:

$$573 \quad M^1(Q^2, Q^1) = \frac{E^1(Q^2)}{E^1(Q^1)} = \frac{OQ_{froniter1}^2 / OQ^2}{OQ_{froniter1}^1 / OQ^1} \quad (19)$$

574

575 Taking production frontier 2 as the benchmark, the Malmquist productivity index
 576 of Q is:

577
$$M^2(Q^2, Q^1) = \frac{E^2(Q^2)}{E^2(Q^1)} = \frac{OQ_{\text{froniter2}}^2 / OQ^2}{OQ_{\text{froniter2}}^1 / OQ^1} \quad (20)$$

578 Thus, two different Malmquist productivity indices of Q are produced by referring
 579 to frontier 1 and frontier 2, respectively. Based on the method proposed by Caves et al.
 580 (1982), Fare et al. (1992) used the geometric average of the two Malmquist indices as
 581 the Malmquist productivity index of the evaluated DMU, i.e.:

582
$$M(Q^2, Q^1) = \sqrt{\frac{E^1(Q^2)}{E^1(Q^1)} \frac{E^2(Q^2)}{E^2(Q^1)}} = \sqrt{\frac{OQ_{\text{froniter1}}^2 / OQ^2}{OQ_{\text{froniter1}}^1 / OQ^1} \frac{OQ_{\text{froniter2}}^2 / OQ^2}{OQ_{\text{froniter2}}^1 / OQ^1}} \quad (21)$$

583

584 So, the Malmquist productivity index of $DMU_0(x_0, y_0)$ from period t to $t+1$
 585 can be expressed as:

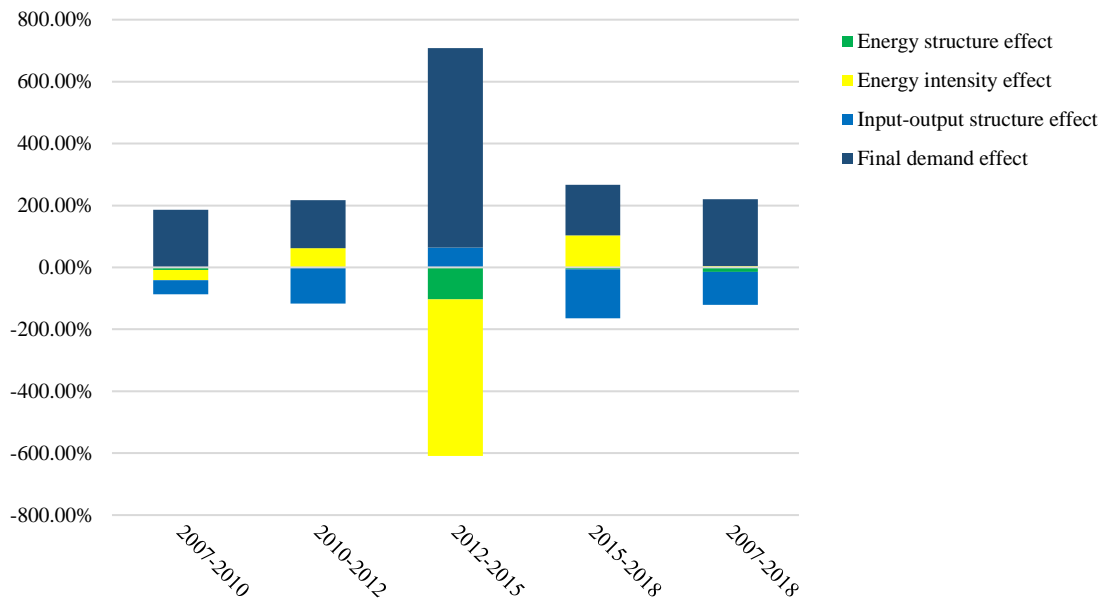
586
$$M(x_0^{t+1}, y_0^{t+1}, x_0^t, y_0^t) = \sqrt{\frac{E^t(x_0^{t+1}, y_0^{t+1})}{E^t(x_0^t, y_0^t)} \frac{E^{t+1}(x_0^{t+1}, y_0^{t+1})}{E^{t+1}(x_0^t, y_0^t)}} \quad (22)$$

587 4 Results

588 4.1 Decomposition analysis of CO₂ emissions from thermal electricity and heating 589 sector

590 Fig. 3 shows the impact of the four factors on CO₂ emissions in China's thermal
 591 electricity and heating sector from 2007 to 2018. These four factors have different
 592 effects on CO₂ emissions at different stages. Overall, the final demand effect was
 593 responsible for the majority of the growth in CO₂ emissions; the figure increased by
 594 6.835 billion tons from 2007 to 2018. The energy intensity effect increased CO₂
 595 emissions by 115 million tons, accounting for 3.64 per cent of the total effect. However,
 596 the energy structure effect and the input-output structure effect helped to reduce
 597 emissions, with the input-output structure effect making the greatest contribution to
 598 reducing carbon emissions resulting from energy production in China. It reduced CO₂
 599 emissions from energy production by 3.834 billion tons, which accounts for 107.14 per
 600 cent of the total effect. Meanwhile, the energy structure effect had a weaker impact on
 601 reducing emissions, with a reduction of 452 million tons, accounting for 14.3 per cent
 602 of the total.

603



604

605 **Fig. 3.** Contribution of four factors to changes in CO₂ emissions during the period 2007-2018

606

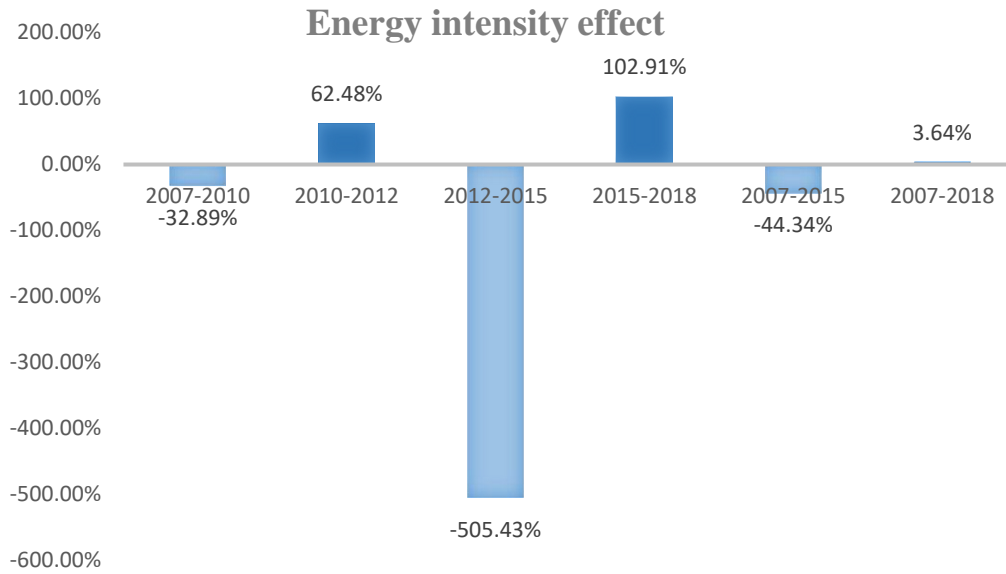
607 The energy intensity effect can be optimised by improving the efficiency of energy
 608 utilisation, which involves adapting the industrial structure and introducing
 609 technological innovation. The input-output structure effect is a reflection of
 610 technological progress. In terms of the long-term reduction in emissions, reducing the
 611 intensity of energy consumption, and optimising the input-output structure both play an
 612 important part. In the short term, controlling the final demand and optimising the energy
 613 structure are effective ways of achieving a reduction in emissions. In the next sections,
 614 we further analyse the mechanisms through which the energy intensity effect and the
 615 final demand effect operate to reduce carbon emissions.

616 *4.2 Analysis of the mechanisms by which the four factors reduce emissions*

617 In this subsection, we analyse the emission reduction mechanisms used by the four
 618 drivers of change in relation to the thermal power and heating sector. Based on the
 619 research findings, we put forward corresponding policy recommendations.

620 *4.2.1 Analysis of the emission reduction mechanism of the energy intensity effect*

621 Our results show that, overall, the energy intensity effect increased CO₂ emissions
 622 from 2007 to 2018. However, the energy intensity effect declined from 2007 to 2015,
 623 although there was an increase between 2010 and 2012 (see Fig. 4). This implies that
 624 the energy policy applied to the thermal power and heating sector during the 12th period
 625 of the five-year plan (2011-2015) had a generally positive effect on reducing emissions,
 626 but in specific years, the energy intensity deviated from the policy target, which is also
 627 proved by the energy intensity coefficient shown in Fig. 5.



628

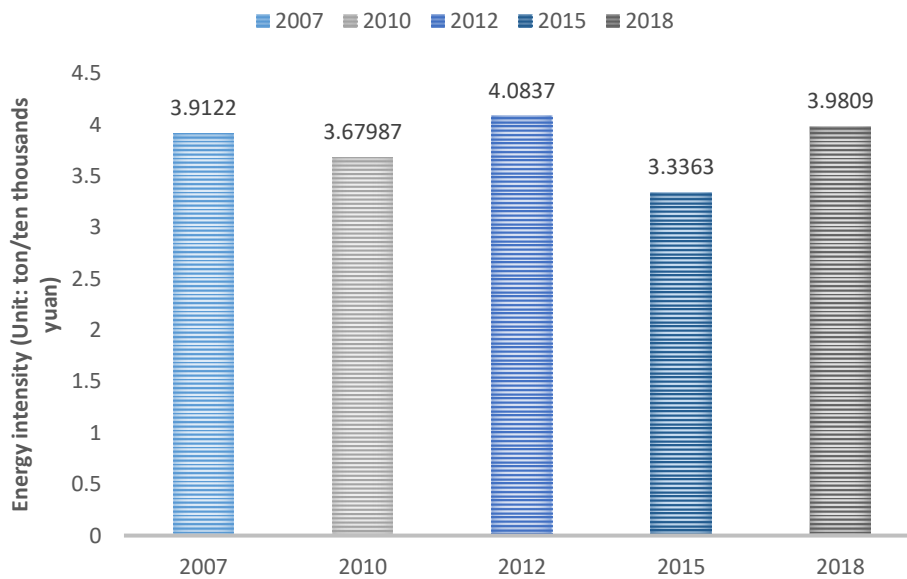
629 *Note:* The dark blue represents increments in emissions, the light blue represents
 630 reductions in emissions (similarly hereafter).

631

Fig. 4. Energy intensity effect during the period 2007-2018

632

633



634

635 **Fig. 5.** Energy intensity coefficient of thermal electricity and heating sector during the
 636 period 2007-2018

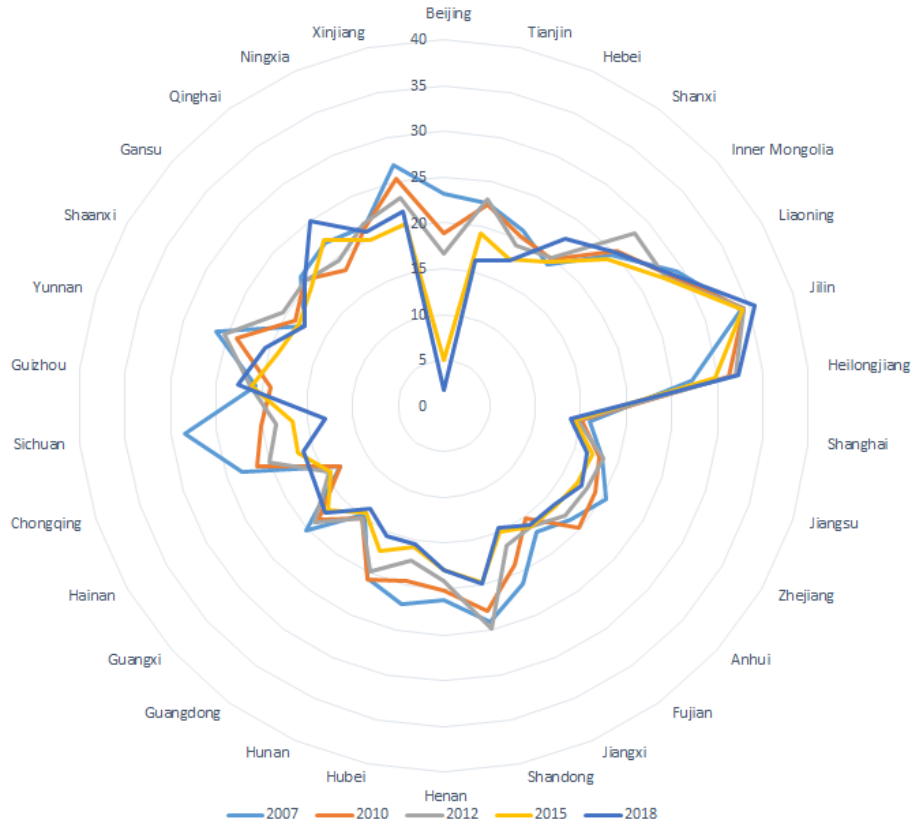
637

638 During the 11th period of the five-year plan (2006-2010), the Chinese government
 639 set a mandatory target of reducing energy intensity by 20%. Both the decline in carbon
 640 intensity and the reduction in emissions confirmed the effectiveness of the energy

641 policies. During the 12th period of the five-year plan, the government introduced a more
642 stringent mechanism for controlling the total energy consumption, and set carbon
643 intensity targets for each province. Overall, these policies achieved their goals; however,
644 it is worth considering why the period from 2010 to 2012 witnessed a deviation from
645 the generally positive trend. Moreover, Fig. 4 and Fig. 5 show that the energy intensity
646 coefficient and its effect on emissions increased significantly during the 13th period of
647 the five-year plan (2016-2020), which implies that the energy intensity of the thermal
648 power sector did not fulfil the policy expectations.

649 As mentioned above, it is noteworthy that the energy intensity of China's thermal
650 electricity and heating sector increased between 2010 and 2012, thereby offsetting most
651 of the beneficial effects of the policy. Identifying the causes of this reversal can help to
652 provide guidance for formulating more effective energy policies in the future. From the
653 analysis of relevant data, we found the following possible explanations: First,
654 consumption of raw coal during the three periods under study was 16.87, 21.04 and
655 3.35 million tons, respectively. Compared to the period from 2007 to 2010, the amount
656 of low-carbon energy used, such as natural gas, fell by half, while the amount of
657 liquefied natural gas dropped by 93.5 per cent during the period from 2010 to 2012.
658 Therefore, the dramatic increase in the use of raw coal and the sharp decline in low-
659 carbon energy use were the major factors that led to the significant increase in energy
660 intensity between 2010 and 2012. From 2012 to 2015, the country began to vigorously
661 promote the policy of clean energy substitution, and the use of raw coal was
662 significantly reduced to only 16 per cent of the total for the preceding period, while the
663 use of low-carbon energy increased threefold compared with that of the period from
664 2010 to 2012. Second, during the 11th period of the five-year plan (2006-2010), the
665 Chinese government set a mandatory target of reducing energy intensity by 20 percent
666 from the 2005 level. During this period, inefficient and technologically backward small
667 thermal electricity units were forced to close. This policy improved the energy
668 efficiency of the thermal electricity sector, which saw a reduction in carbon emissions
669 of 1.74 billion tons from 2005 to 2010. Moreover, as a result of the global financial
670 crisis in 2008, China's economic growth slowed down from 2008 to 2009, and the
671 growth rate of primary energy consumption dropped sharply. This also reduced the
672 energy intensity in the thermal electricity sector to a certain extent.

673 In order to analyse the causes of changes in energy intensity in more detail, we
674 calculated the energy intensity values of the thermal electricity and heating sector for
675 30 provinces from 2007 to 2018. As the annual output values of the thermal electricity
676 and heating sector for some of the provinces are not released in the Statistical Yearbook,
677 we used the measure of CO₂ emissions per unit of power generation to approximate the
678 energy intensity values. The results are shown in Fig. 6 and Table 4.



679

680 **Fig. 6.** CO₂ emissions per unit of electricity generated in the thermal electricity and
 681 heating sector for 30 provinces during the period 2007-2018 (unit: 10⁴t / 10⁸ kW·h)

682 Fig. 6 shows that, apart from Hainan province, the CO₂ emissions per unit of
 683 electricity generated by the thermal electricity and heating sector in Beijing, Tianjin,
 684 Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong (most of the eastern
 685 region) followed a downward trend from 2007 to 2018, and the average rate of decline
 686 for these provinces was 22.8 percent. In the eastern region, Beijing experienced the
 687 biggest drop of 92.24 percent. In the central region, Shanxi's CO₂ emissions per unit
 688 of electricity rose by 17.6 percent from 2007 to 2018. In the northeastern region, the
 689 CO₂ emissions per unit of electricity generated by Liaoning, Jilin and Heilongjiang
 690 were much higher than those of the other provinces. More specifically, Jilin and
 691 Heilongjiang's emissions increased from 34.16 and 27.19 to 35.65 and 32.39,
 692 respectively. The CO₂ emissions per unit of electricity of these two provinces increased
 693 by 4.36 percent and 19.15 percent, respectively, between 2007 and 2018. In terms of
 694 the western region, Inner Mongolia, Guizhou, Shanxi and Qinghai showed an upward
 695 trend, while the other provinces saw an average decline of 18.78 percent, and Sichuan
 696 experienced the most dramatic decline of 54 percent.

697 From an overall regional perspective, the CO₂ emissions per unit of electricity
 698 generated by the thermal electricity and heating sector in the northeastern region were
 699 much higher than those of the other regions during the period 2007-2018 (see Table 4).
 700 The western region produced the second highest level of CO₂ emissions per unit of
 701 electricity, which was higher than the national average level during the same period.

702 The central and eastern regions ranked third and fourth, respectively, meaning that they
703 produced less than the national average level during the same period..

704

705 **Table 4**

706 CO₂ emissions per unit of electricity generated in the thermal electricity and heating sector during the
707 period 2007-2018 (unit: 10⁴t / 10⁸ kW•h)

Region	2007	2010	2012	2015	2018
Eastern region	19.41	18.66	18.85	16.95	16.69
Central region	20.31	19.94	18.81	17.48	17.94
Western region	22.95	21.96	23.19	20.66	21.46
Northeastern region	29.64	30.58	30.53	29.79	31.27
Whole country	21.22	20.60	20.76	18.87	19.14

708

709 From 2010 to 2012, due to the relative backwardness of the western region and a
710 reliance on the enrichment of resources, the GDP growth of the northwestern provinces
711 increasingly came to depend on the development of coal-related industries. With the
712 introduction of a series of national stimulus policies after the financial crisis, economic
713 growth began to recover, accompanied by an increase in demand for electricity. Coupled
714 with the relatively moderate energy intensity reduction targets set for the western
715 provinces, these provinces were unable to suppress the increase in energy supply. From
716 2010 to 2012, the construction of coal bases within the western provinces accelerated.
717 These coal bases comprised 10 large-scale coal enterprises with a capacity of 100
718 million tons and 10 smaller coal enterprises with a capacity of 50 million tons, and they
719 produced more than 90 percent of the country's total coal output. In fact, during the 11th
720 period of the five-year plan, some of these coal bases had already started operating, and
721 were producing a considerable yield. The unprecedented scale of coal mining has been
722 accompanied by large-scale coal-fired electricity generation and coal-chemical projects
723 involving high levels of energy consumption. These industrial clusters have developed
724 rapidly in the western provinces and regions, thereby forming a so-called 'energy base'.
725 This is also the main reason for the substantial increase in the coal consumption of
726 thermal electricity from 2010 to 2012. Table 4 shows that the CO₂ emissions per unit
727 of electricity rose from 21.96 in 2010 to 23.19 in 2012, which also confirms this
728 conclusion.

729 In 2012, the energy development plan for the 12th period of the five-year plan was
730 finally proposed. During this period (2011-2015), the government gradually established
731 an effective and reasonable mechanism to control the total amount of energy used. It
732 was planned that China's total energy consumption should stabilise at about 4.1 billion
733 standard tons in 2015. In the future, the government would levy a tax on fossil energy
734 consumption. The plan also set a target for each province to reduce its energy intensity,
735 with the western regions including Ningxia, Inner Mongolia and Gansu aiming for a 15
736 per cent reduction, and the eastern regions of Jiangsu, Zhejiang and Guangdong trying
737 to achieve an 18 per cent reduction. These measures have significantly reduced coal

738 consumption and carbon intensity in the thermal electricity and heating sector. In
739 addition, the average price of thermal coal at the end of 2011 had nearly tripled to in
740 excess of 850 yuan/ton, compared with 227 yuan/ton in 2000. Soaring coal prices have
741 caused huge losses in the downstream thermal electricity industry, and the demand for
742 coal has also been greatly reduced. It also clearly shows that there was a significant
743 decline in the CO₂ emissions per unit of electricity from 2012 to 2015.

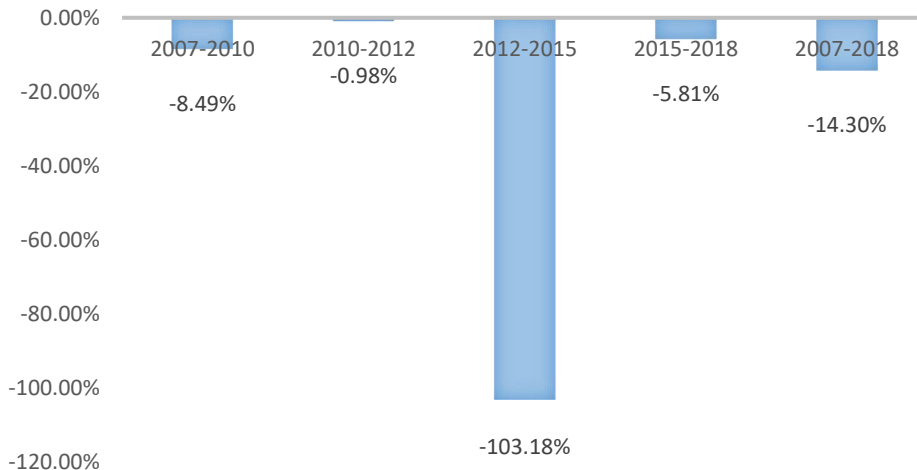
744 On 18th June 2019, the People's Daily announced that China's energy intensity had
745 dropped by 11.35 per cent since the implementation of the 13th five-year plan (2016-
746 2020), and the dual control target for energy consumption and energy intensity met the
747 scheduled requirements of the 13th five-year plan. However, the energy intensity of the
748 thermal electricity and heating sector did not show a downward trend from 2015 to
749 2018. Table 4 shows that, except for the eastern region, CO₂ emissions per unit of
750 electricity in other regions increased, especially in the northeastern and western regions.
751 Shanxi province in the western region experienced the largest increment, with an
752 increase of 3.03. This may be due to the significant increase in the installed capacity of
753 thermal power, resulting in a significant increase in fossil energy consumption. Since
754 2016, the installed capacity of thermal power has maintained a rapid growth rate. By
755 the end of September 2017, the installed capacity of thermal electricity in China had
756 reached 1.08 billion kilowatts, which is close to the red line set in the Thirteenth Five-
757 Year Plan. Table 1 shows that the energy use of raw coal in the thermal electricity and
758 heating sector rose from 1.43 billion tons of standard coal in 2015 to 1.66 billion tons
759 of standard coal in 2018. In November 2017, Polaris power grid reported that the supply
760 of thermal electricity had greatly increased, and there was an obvious imbalance
761 between supply and demand. In the future, the energy policy aims to achieve a balance
762 between stock adjustment and incremental optimisation in the thermal electricity sector
763 on a regional basis. Striking a balance between clean energy development and fossil
764 energy utilisation may help to reduce energy intensity.

766 *4.2.2 Analysis of the emission reduction mechanism of the energy structure effect*

767 As shown in Figure 7, the energy structure effect has continuously reduced
768 emissions by 8.49%, 0.98% , 103.18% and 5.18%, respectively, during the four periods
769 studied. Between 2010 and 2012, the emission reduction effect was relatively small.
770 However, it then significantly improved during the period from 2012 to 2015. To reveal
771 the reasons behind this phenomenon, we further analysed the energy use in the thermal
772 power sector between 2007 and 2018 and measured the carbon emission factors after
773 the conversion of various energies into standard coal. Based on the energy use in the
774 thermal electricity generation and heating sector shown in Table 1, we obtained the
775 incremental consumption of each energy combustion unit in the thermal electricity and
776 heating sector from 2007 to 2018, which is shown in Table 5 (unit: 10,000 tons).

777

Energy structure effect



778

779

Fig. 7. Energy structure effect during the period 2007-2018

780

781 Table 5 shows that, compared with the period 2007-2010, there was a dramatic
 782 increase in the consumption of high-carbon energy, such as raw coal, between 2010 and
 783 2012; while the consumption of low-carbon energy such as blast furnace gas markedly
 784 declined. This may explain the relatively weak reduction in the contribution of the
 785 energy structure effect. During the period from 2012 to 2015, the consumption of raw
 786 coal dramatically declined, while the consumption of blast furnace gas and natural gas
 787 grew markedly, which could help to explain the significant reduction in emissions
 788 caused by the energy structure effect. From 2015 to 2018, the increase in the
 789 consumption of raw coal slowed down, while increments in the consumption of blast
 790 furnace gas and natural gas remained low. During the period from 2015- 2018, the
 791 consumption of raw coal was relatively higher than the period from 2007-2010 and the
 792 consumption of low-carbon energy is smaller. Therefore, the effect of the energy
 793 structure on reducing emissions during the period 2015 to 2018 was weaker than for
 794 the period from 2007 to 2010. The results shown in Table 5 also imply that the
 795 consumption of raw coal has a big impact on carbon emissions. The large swings in raw
 796 coal consumption between 2007 and 2015 may be due to the fact that the construction
 797 of coal bases in the western provinces accelerated during the period from 2010 to 2012,
 798 thereby greatly increasing the supply of coal. In 2012, the 12th period's five-year energy
 799 development plan imposed mandatory controls on coal consumption. At the same time,
 800 coal prices rose, and low-carbon energy was increasingly used to replace raw coal.
 801 These developments led to a significant reduction in the energy structure effect between

2012 and 2015. In addition, the consumption of high-carbon energy such as washed coal, diesel oil, and fuel oil, declined relatively slowly; while the consumption of low-carbon energy such as blast furnace gas grew steadily, which also helps to explain the effect of changes in the energy structure. It can therefore be concluded that the energy structure effect has succeeded in reducing the emissions generated by China's thermal electricity and heating sector, perhaps due to the continual optimisation of the energy consumption structure.

809

810 **Table 5**

811 Increments in energy consumption (unit: 10⁴ tce) from 2007 to 2018.

Categories of energy	Adjusted CO ₂ emission factors (t CO ₂ /t tce)	Adjusted			
		2007-2010	2010-2012	2012-2015	2015-2018
Raw Coal	3.37	16872.88	21039.71	3347.37	23093.35
Cleaned Coal	2.87	-26.78	77.25	-11.88	-79.07
Other WashedCoal	2.29	93.08	-197.84	-14.81	688.77
Coke	1.36	0.00	0.00	273.89	0.00
Coke Oven Gas	3.13	5096.84	1640.83	1452.85	-253.23
Blast Furnace Gas	0.13	14818.96	3650.05	8356.69	-29.06
Converter Gas	1.06	1793.37	1600.66	237.52	10304.33
Other Gas	0.59	-11661.00	0.00	228.39	3662.86
Crude Oil	0.20	-13.60	7.47	9.90	-142.14
Gasoline	2.51	-0.06	-0.01	0.24	0.00
Kerosene	2.15	0.00	0.00	0.00	-5.50
Diesel Oil	2.05	-165.75	-116.06	-13.74	-0.25
Fuel Oil	2.10	-531.21	-135.43	-48.26	0.00
LPG	2.17	-7.29	-1.39	5.49	4.31
Refinery Gas	2.27	136.00	-67.55	-38.77	-174.26
Other Petroleum Products	1.85	-88.84	-122.60	21.04	1.27
Natural Gas	1.69	1088.61	583.04	1412.27	76.92
LNG	2.55	310.09	19.59	-25.76	-28.96

812

813

814 Next, we further analysed the impacts of the changes in energy structure on CO₂

815 reduction between 2007 and 2018 and disclosed the contribution of each energy source
816 to carbon reduction. On the basis of the SDA decomposition, we continued to
817 decompose the contribution of each energy source to reducing carbon emissions. The
818 emissions reduction for each type of energy is shown in Table 6 (unit: 10,000 tons).

819 **Table 6**

820 Emissions reduction for each type of energy (unit: 10⁴ t) from 2007 to 2018.

Categories of energy	2007-2010	2010-2012	2012-2015	2015-2018	2007-2018
Raw Coal	-20739.51	-3256.77	-31186.26	-20358.96	-87841.19
Cleaned Coal	-113.01	238.36	-65.40	-303.07	-231.12
Other Washed Coal	-1020.48	-2361.13	-630.04	2323.54	-2907.74
Coke	0.00	0.00	860.07	0.00	0.00
Coke Oven Gas	5372.58	-450.20	611.70	-926.23	58.60
Blast Furnace Gas	8213.76	506.70	3985.14	-3931.67	4343.37
Converter Gas	7519.44	5386.38	-225.40	2736.61	19698.05
Other Gas	-5989.46	0.00	101.43	12427.92	29273.82
Crude Oil	-33.57	10.10	15.83	-79.94	-8829.70
Gasoline	-0.14	-0.06	0.34	0.00	0.00
Kerosene	0.00	0.00	0.00	-19.82	-38.77
Diesel Oil	-415.75	-257.71	-33.62	-0.46	-0.35
Fuel Oil	-1447.52	-430.19	-154.72	0.00	0.00
LPG	-8.70	-1.59	5.45	-7.16	-976.22
Refinery Gas	80.20	-145.63	-72.01	-448.32	-3264.51
Other Petroleum Products	-302.28	-322.84	41.53	0.13	-8.79
Natural Gas	1278.88	245.23	1943.67	19.73	-120.37
LNG	376.85	-46.66	-69.20	-83.77	-879.37
Total reduction effect	-7228.72	-886.01	-24871.51	-6731.17	-45176.8

821

822 Table 6 clearly shows that different energy sources had differing impacts on
823 reducing emissions from China's electricity and heating industries between 2007 and
824 2018. Changes in energy structure, involving a reduction in the use of raw coal, cleaned
825 coal, other washed coal, crude oil, kerosene, diesel oil, LPG, refinery gas and other
826 petroleum products, natural gas and LNG had significant effects on emissions reduction
827 in China's thermal electricity and heating sector during this period. Between 2007 and
828 2010, increments in the use of coke oven gas, blast furnace gas, converter gas, refinery
829 gas, natural gas and LNG increased CO₂ emissions. From 2010 to 2012, the increase in
830 cleaned coal, blast furnace gas, converter gas, crude oil, and natural gas had a positive
831 effect on CO₂ emissions. From 2012 to 2015, the increases in coke, coke oven gas, blast
832 furnace gas, other gas, crude oil, LPG, other petroleum products and natural gas had

833 the effect of raising CO₂ emissions. From 2015 to 2018, the increase in other washed
 834 coal, converter gas, other gas, other petroleum products and natural gas caused a
 835 corresponding increase in CO₂ emissions. These results further confirm that increasing
 836 the consumption of low-carbon energy, such as blast furnace gas and converter gas, and
 837 cutting down the use of raw coal, contributes to emissions reduction.

838 The following conclusions can be drawn. First, from 2012 to 2015, energy
 839 structure optimisation had the most significant effects on reducing emissions, while the
 840 period from 2007 to 2010 and the period from 2015 to 2018 saw a smaller reduction.
 841 Changes in the energy structure during the period from 2010 to 2012 had the least effect
 842 on reducing emissions. Second, increasing the consumption share of low-carbon energy
 843 is conducive to reducing emissions. In addition to reducing raw coal, cleaned coal, other
 844 washed coal, crude oil and refinery gas, decreasing the proportion of high-carbon
 845 energy sources, such as diesel oil, kerosene and other petroleum products, had limited
 846 effects on emissions reduction. Therefore, the reduction in emissions from China's
 847 thermal electricity and heating sector as a result of adjusting the energy structure was
 848 mainly caused by the increased share of low-carbon energy, while the emissions
 849 reduction effect was relatively small in the case of high-carbon energy, such as diesel
 850 oil, kerosene and other petroleum products.

851 This study then further explored how the energy structure in China's thermal
 852 electricity and heating sector could be optimised. Based on Sun and Huang's (2021)
 853 study, the SBM-DEA model that treats CO₂ as an unexpected output was introduced to
 854 estimate the slack variables for the 30 provinces from 2007 to 2018. Studying the slack
 855 variables is helpful in terms of discovering the causes of energy efficiency loss and can
 856 thus provide a scientific reference for adjusting the energy structure. Table 7 presents
 857 the results of the energy efficiency and the slack variables in relation to China's thermal
 858 electricity and heating sector from 2007 to 2018. The average energy efficiency values
 859 for all 30 provinces in each period are all less than 1, which means the energy structure
 860 needs to be further optimised.

861

862 **Table 7**

863 Energy efficiency and slack variables from 2007 to 2018.

Year	Score	Slack variables (unit: 10 ⁴ tec)				
		Total Coal	Petroleum Products	Gas	Coal gas	CO ₂ (10 ⁴ tons)
2007	0.924	-23.98	-4.30	-1.00	-86.93	-119.69
2010	0.921	-16.19	-6.75	-4.87	-121.25	-116.03
2012	0.955	-22.36	-5.71	-2.85	-37.58	-133.44
2015	0.947	-31.78	-3.90	-1.81	-67.17	-140.18
2018	0.933	-19.74	-3.88	-2.63	-102.83	-312.79

864 Note: The 20 energy sources are divided into four major categories and converted into standard coal.

865

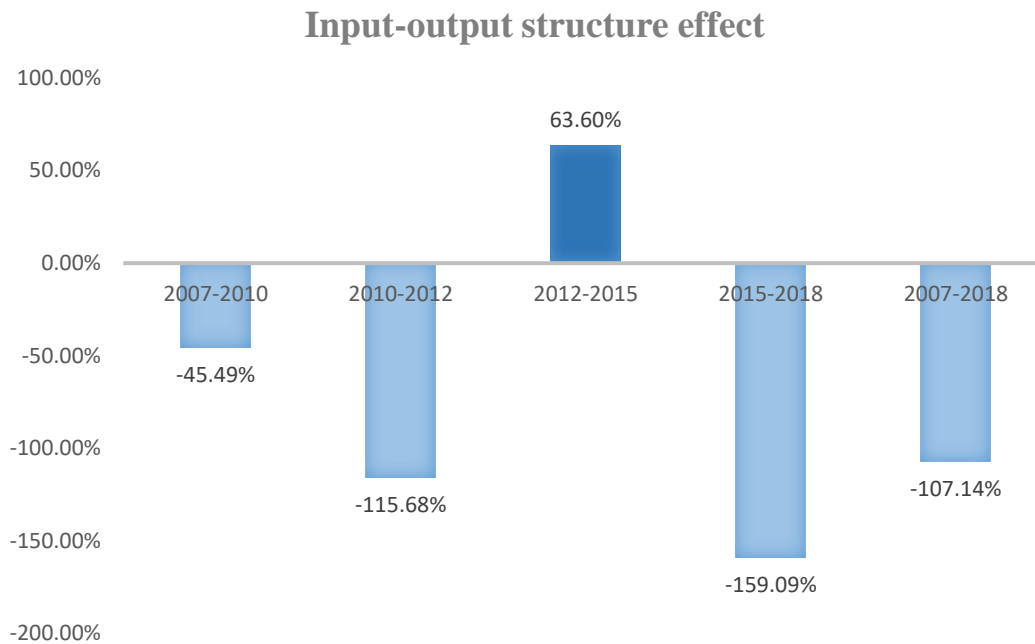
866 In 2007, the total coal, petroleum products, gas and coal gas had a redundancy of
 867 239,776 tec, 42,977 tec, 10,035 tec and 869,267 tec, respectively. Meanwhile, CO₂
 868 emissions had a redundancy of 0.12 million tons. To achieve the energy efficiency target

869 for 2010, the thermal electricity and heating sector needed to reduce its consumption of
870 total coal, petroleum products, gas and coal gas by 161,875 tec, 67,507 tec, 48,719 tec
871 and 1,212,539 tec, respectively. In the same year, CO₂ emissions had a redundancy of
872 0.116 million tons. In 2012, the consumption of total coal, petroleum products, gas and
873 coal gas had a redundancy of 2,336,063 tec, 57,081 tec, 28,504 tec and 375,772 tec,
874 respectively. CO₂ emissions can be reduced by 0.133 million tons when the energy
875 efficiency reaches the optimal value. For 2015, the total coal, petroleum products, gas
876 and coal gas had a redundancy of 239,776 tec, 42,977 tec, 10,035 tec and 869,267 tec,
877 respectively, while CO₂ emissions had a redundancy of 0.12 million tons. Similarly, the
878 input redundancy values of various energy sources and the CO₂ emissions reduction in
879 2015 and 2018 can be obtained from the data shown in Table 7. In summary, the value
880 of energy efficiency was at its highest in 2012, out of all the five periods, and the energy
881 efficiency value is consistent with the effect of the energy structure on emissions
882 reduction to a certain extent from 2007 to 2018. In addition, the redundancy values of
883 coal-related products were relatively large in each of the periods studied, which implies
884 that the input of coal-related products should be reduced.

885 *4.2.3 Analysis of the contribution of the input-output structure effect*

886 The input-output structure effect was derived by changing the Leontief inverse.
887 The elements of the Leontief inverse indicate the impact of a unit change in the
888 exogenous final demand on the output of the industry. In addition, each element in the
889 Leontief inverse reflects the direct and indirect effects arising from the interdependence
890 of sectors or industries in the production of goods and services to meet the final demand.
891 The traditional view usually treats the Leontief inverse matrix as the final form of the
892 direct consumption coefficient matrix in order to capture the linkages between sectors
893 or industries and measure technological progress and changes in production structure.
894 For policy and planning purposes, Stone and Brown (1962) suggest that the direct
895 consumption coefficient can be further decomposed using the RAS method into the
896 substitution effect and fabrication effect to reflect the change in the production
897 substitution rate and the technical level, respectively. Dietzenbacher and Los (1998)
898 combined the RAS method and the SDA model to decompose the direct consumption
899 coefficient matrix and calculated the production substitution rate and technical level in
900 specific units. To improve the efficiency and scope of the RAS method, Tho (1998)
901 directly applied the RAS procedure to the Leontief inverse and decomposed the
902 substitution and fabrication factors.

903 The Leontief inverse is a powerful tool in I-O analysis. It plays an important role
904 in economic impact studies, structural change analysis and the identification of key
905 sectors for development planning. In our study, the input-output structure effect
906 comprehensively reflects the efficiency of the production technology and production
907 structure used in thermal electricity production. Fig. 8 shows that, in the first two
908 periods and the fourth period, the input-output structure had the effect of reducing
909 emissions. This indicates that the country's determination to push forward the upgrading
910 of thermal electricity generation technology has made substantial progress. However,
911 during the period from 2012 to 2015, the input-output structure effect became a driver
912 for increasing carbon emissions.



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Fig. 8. Input-output structure effect during the period 2007-2018

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Due to the lag in the market reform of the industrial development mechanism and the rise in coal prices, electricity generation enterprises have suffered continuous losses since 2011. Electricity generation companies are not optimistic about the prospect of being able to make a profit from thermal electricity and there have been no significant breakthroughs in the reform of the national electricity system. Therefore, thermal electricity enterprises started to significantly reduce both investment and electricity generation, leading to a reduction in the utilisation rate of thermal electricity equipment and a significant weakening of the effect of technological upgrading and the scale effect. According to data released by the China electricity council, in the first quarter of 2012, the country produced an additional 6.49 million kilowatts of thermal electricity, which is 3.52 million kilowatts less than in the preceding year. In 2014, investment in thermal electricity was significantly lower than that of wind-powered electricity and hydroelectricity. Furthermore, given the slow growth rate of the national installation capacity in 2015 and the decline in the growth rate of electricity consumption under the “New Normal”², the utilisation hours of equipment for the industry as a whole did not improve significantly until 2015. The Malmquist total factor production index for the adjacent base period shown in Table 8 indicates that the productivity of the thermal electricity sector decreased during the period 2012-2015, which proves that the effect of upgrading technology in the thermal electricity sector was not very effective.

² ‘New Normal’ refers to a sustainable medium to high growth stage. The economic growth rate in 2015 was relatively low, and it suppressed the demand and consumption.

936

937 **Table 8**

938 Malmquist total factor production index for adjacent base period.

Time span	Malmquist total factor production index	Technical efficiency change	Technological change
2007-2010	1.1551	1.0387	1.1039
2010-2012	1.0564	1.0854	0.9661
2012-2015	0.9998	1.0081	0.9997
2015-2018	1.1630	1.0075	1.1579

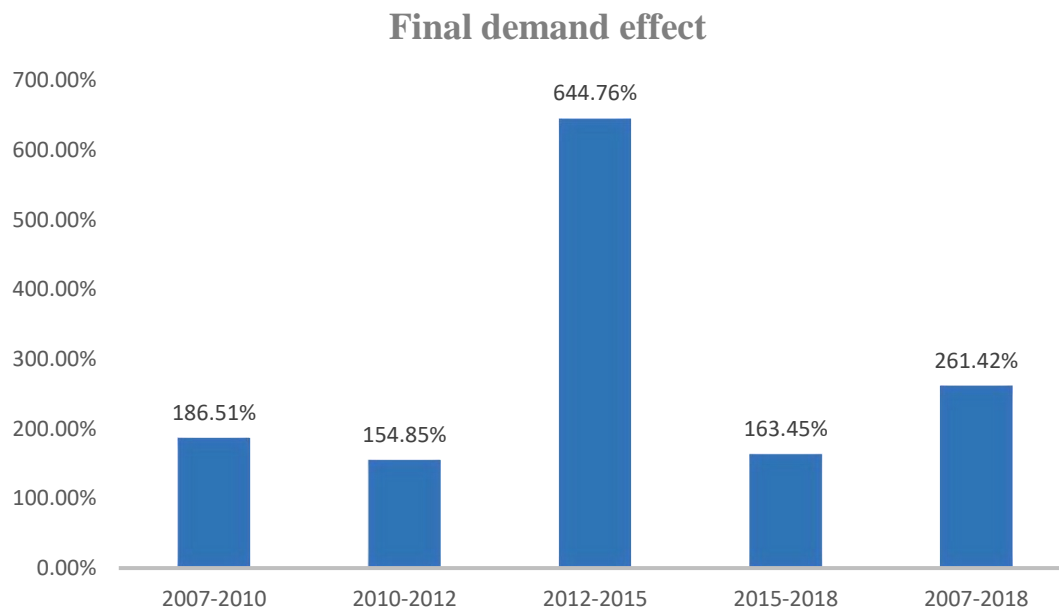
939 Note: A Malmquist index greater than 1 indicates an increase in productivity, while an index less than 1 indicates a decrease in
940 productivity.

941

942 *4.2.4 Analysis of the contribution of the final demand effect*

943 Figure 9 shows that the final demand effect is one of the main driving forces behind
944 the increase in CO₂ emissions in China's thermal electricity and heating sector, and that
945 it continues to increase.

946



947

948 **Fig. 9.** Final demand structure effect between 2007 and 2018

949

950 Next, the study specifically analysed the contribution of the scale change in each
951 industry to the growth in carbon emissions generated by the thermal electricity and
952 heating sector from 2007 to 2018. The impacts of changes in the scale of various
953 industries on CO₂ emissions in China from 2007 to 2018 are shown in Table 5 (unit:
954 10,000 tons) and Figure 6.

955

956 **Table 9**

957 Impact of changes in final demand of various industries on carbon emissions.

Sector	2007-2010	2010-2012	2012-2015	2015-2018	2007-2018
Service sector	38120.12	28569.87	41800.38	42750.01	181793.88
Heavy industry	62106.87	22890.26	30260.16	9139.25	115215.89
Light industry	17666.58	11259.78	17489.58	1273.01	46383.23
Construction industry	51032.65	34320.07	89889.03	48256.74	234792.06
Chemical industry	664.97	5494.67	1213.90	4075.51	11898.61
Agriculture	-78.53	4971.74	-1490.38	2955.11	6499.13
Transportation industry	-2782.98	7023.59	-978.22	7850.94	12905.97
Fossil energy sector	-7622.42	-2068.26	9919.88	-8417.06	-8532.81
Electricity sector	-353.21	27939.34	-32684.84	81628.54	82567.38
Total	158754.05	140401.05	155419.49	189512.04	683523.33

958

959 Table 9 and Figure 9 show the impact of changes in China's industrial demand on
960 the growth of CO₂ emissions from 2007 to 2018. It can be seen that the scale of
961 industrial expansion within the service sector played a dominant role in promoting the
962 growth of CO₂ emissions in the thermal electric and heating sector during the period
963 from 2007 to 2018. Regarding the final demand effect, the fossil energy, transport,
964 agriculture and electricity sectors all experienced a reduction in emissions between
965 2007 and 2010. During the periods 2010-2012 and 2015-2018, fossil energy continued
966 to play a role in reducing CO₂ emissions, but the other sectors all contributed to an
967 increase in CO₂ emissions. From 2012 to 2015, the growth of demand in the service
968 industry, the construction industry, heavy industry and light industry played a major
969 part in the increase in CO₂ emissions, while the transport industry, agriculture and the
970 electric power industry contributed to a reduction in emissions. In terms of the industrial
971 structure, within the secondary industries sector, heavy industry and the construction
972 industry were the major contributors to CO₂ emissions from the thermal electricity and
973 heating sector. However, the contribution of the service industry and agriculture were
974 relatively low. If expansion continues on the same scale, the effect of the primary and
975 tertiary industries (agriculture and services) on increasing CO₂ emissions from electric
976 heating energy will be less than that of the secondary industries (manufacturing).
977 Although the increase in the scale of industrial expansion will lead to an increase in
978 carbon emissions from the electricity and heating sector, increasing the ratio of the
979 primary and tertiary industrial structures is conducive to slowing down the growth rate
980 of carbon emissions from electricity and heating energy.

981

982 **5. Discussion and policy implications**

983 With the continuous growth of China's economy, thermal electricity and heating

984 supply have become one of the most important material foundations of economic
985 development. At the same time, the carbon emissions produced by electricity generation
986 not only have adverse effects on the environment, but also restrict the development of
987 China's economy. In 2015, the electricity industry in China released 48.6 percent of the
988 country's CO₂, of which coal-fired CO₂ emissions accounted for the largest share.
989 During the 11th and 12th periods of the five-year plans, China pursued carbon emission
990 reduction policies aimed at the thermal electricity and heating sector, such as
991 accelerating the upgrading of technology, reducing energy consumption and optimising
992 the energy structure in the thermal and heating sector. Some scholars such as Paul (2016)
993 and Wang (2019) have also focused on thermal electricity and applied the
994 decomposition method to investigating the drivers behind the rise in CO₂ emissions
995 during the period 2002-2012 using aggregated five-yearly data, in an attempt to provide
996 guidance for energy policy. They maintained that the increase in CO₂ emissions from
997 electricity generation during the period 2002-2012 was mainly driven by changes in
998 electricity demand.

999 However, in the decomposition process, they only specified the total effect of
1000 energy structure optimisation and final demand, and ignored the specific amount of
1001 reduction in carbon emissions produced by each energy source and each industrial
1002 sector. Moreover, data that is based on a five-year cycle tends to obscure the mechanism
1003 behind energy policy, and thus may produce misleading results. With the launch of
1004 subsequent economic stimulus policies, China's energy demand underwent a rapid
1005 increase from 2007 to 2018. In order to trade off between economic development and
1006 reducing carbon emissions, and to formulate appropriate future energy policies, it is
1007 crucial to investigate the contribution made by each of the industrial sectors to CO₂
1008 emissions, and assess whether the energy policy is having the desired effect. Based on
1009 our aggregated data decomposition for the three-yearly data, we argue that the
1010 formulation of energy policies should take into consideration the contextual factors
1011 affecting each province and adapt measures to local conditions. The purpose of our
1012 research is to provide policy guidance for formulating a more effective energy policy
1013 that is better suited to the reality of the situation.

1014 From 2007 to 2018, CO₂ emissions from the thermal electricity and heating sector
1015 initially rose and then fell and then increased again, reaching a local peak in 2012. In
1016 general terms, the study shows that the energy structure effect, and the input-output
1017 structure effect are the main factors which account for the overall reduction in CO₂
1018 emissions between 2007 and 2018. In particular, advances in electricity generation
1019 technology have played a prominent role in reducing CO₂ emissions. The demand effect
1020 caused by the expansion in the scale of the economy was the main factor driving the
1021 increase in CO₂ emissions from 2007 to 2018. The energy intensity effect had a weak
1022 effect on increasing CO₂ emissions from 2007 to 2018.

1023 In addition, we also found that the ongoing upgrading of technology used in
1024 thermal power generation has not played a very important role in reducing emissions.
1025 In other words, in order to be effective, the technology upgrading effect needs to be
1026 accompanied by the market reform of thermal power prices. For example, between 2007
1027 and 2015, the input-output structure effect had the largest impact on emissions reduction

1028 in the thermal electricity and heating sector. This shows that China's long-term policy
1029 of encouraging technological innovation in electricity production has had significant
1030 positive effects. The implementation of new technologies not only reduces energy
1031 consumption, but also curbs the rise in carbon emissions. Moreover, technological
1032 innovation affects the input-output structure of each sector of the national economy.
1033 Changes in the input-output structure will reduce the input of products that generate
1034 high carbon emissions, thus helping to achieve the goal of reducing carbon emissions.
1035 However, the effect of technology on emissions transformed from a positive to a
1036 negative one during the period between 2012 and 2015. The explanation for this lies in
1037 the fact that the market reform of thermal power prices lags behind that of coal prices,
1038 resulting in a conflict between the marketised coal system and the nationally planned
1039 electricity system, which has worsened in recent years. With the rise in coal prices,
1040 thermal electricity enterprises suffered serious losses, which led to a substantial
1041 reduction in investment and electricity generation. This in turn resulted in a significant
1042 reduction in the utilisation rate of thermal electricity equipment and a significant
1043 reduction in the scale effect and the effect of technological upgrading. This finding
1044 indicates that policymakers should accelerate the market-oriented reform of electricity
1045 prices, otherwise efforts to vigorously promote the upgrading of technology may be
1046 counterproductive. In addition, technological innovation requires substantial and
1047 sustained capital investment. The government could provide this through tax collection
1048 to reduce the research and development (R&D) costs of enterprises and stimulate
1049 further R&D.

1050 Under China's strict energy intensity reduction target policy, the energy intensity
1051 rebounded significantly in 2012. Although the energy intensity effect was the second
1052 most important factor accounting for emissions reduction during the period from 2007
1053 to 2015, it nonetheless became a driver of emissions growth between 2010 and 2012.
1054 In addition, according to the overall decomposition results for the period from 2007 to
1055 2018, energy intensity had a weak effect on increasing CO₂ emissions. During the 11th
1056 period of the five-year plan (2006-2010), the Chinese government set a mandatory
1057 target of reducing energy intensity by 20%. During the 12th period of the five-year plan
1058 (2011-2015), the government set targets for individual provinces to reduce their energy
1059 intensity. However, a breakdown of the results shows that energy intensity increased
1060 significantly between 2010 and 2012, becoming the main driver of carbon emissions.
1061 This is probably due to the large coal reserves and backward economy in the western
1062 region of China, and the fact that GDP growth in the northwestern provinces became
1063 increasingly dependent on the development of coal-related industries. In the face of
1064 surging coal consumption and industrial electricity consumption, these western
1065 provinces have been unable to resist the temptation of rising demand and have greatly
1066 increased their mining activity. This implies that the government should focus on
1067 accelerating energy substitution and the upgrading of technology in the western region;
1068 however, in fact this could have a negative impact if the policy objectives are
1069 inconsistent with the reality of the situation. During the 13th period of the five-year plan
1070 (2016-2020), the increase in energy intensity may have been due to the significant
1071 increase in the installed capacity of thermal power, resulting in a significant increase in

1072 fossil energy consumption. To resolve this problem, the energy policy aims to achieve
1073 a balance between stock adjustment and incremental optimisation in the thermal
1074 electricity sector on a regional basis, which may prove to be more effective.

1075 The energy structure effect in the thermal electricity and heating sector produced
1076 a sustained reduction in emissions; however, the reduction effect was relatively small.
1077 This confirms that the energy consumption structure in the electricity sector has been
1078 continually optimised, which is due to the strong support for the development of clean
1079 energy provided by the Chinese government. From the numerical value of the energy
1080 consumption structure effect, it can be seen that the utilisation ratio of clean energy in
1081 China is not very high, and its contribution to reducing carbon emissions remains small.
1082 In the future, the Chinese government should continue to support and encourage
1083 enterprises to use clean energy, for example by offering subsidies or tax reductions.

1084 The final demand effect was the main driving force behind CO₂ emissions from
1085 the thermal electricity and heating sector during the period from 2007 to 2018. The
1086 decomposition of the final demand effect suggests that, among secondary industries,
1087 the construction industry was the main contributor. Overall, the amount of electricity
1088 and heating energy used in the secondary industries was generally higher than that in
1089 the primary and tertiary industries. It is vital to maintain a balance between CO₂
1090 emissions and economic development in these sectors. Reducing the demand for
1091 electricity and heating energy from the secondary industries is conducive to
1092 decelerating the growth in carbon emissions from electric and heating energy sources,
1093 which is also in line with China's industrial restructuring policy. In order to adjust the
1094 economic structure and growth pattern, it appears that a circular, energy-saving
1095 economy may be the way forward. By adapting the industrial structure and, as far as
1096 possible, achieving low carbonisation of the final product, the energy demand structure
1097 and energy efficiency can be improved.

1098 In terms of practical implications, first, efforts to develop energy restructuring and
1099 clean energy substitution have become particularly important in order to reduce carbon
1100 emissions in various countries such as China and EU member countries. Due to the
1101 idiosyncracies of the existing electricity supply structure and layout in China's
1102 electricity sector, measuring the impact of energy structure adjustment is of particular
1103 significance for formulating energy policy. Second, this paper investigated the impact
1104 of the energy intensity effect on CO₂ emissions reduction in the thermal electricity and
1105 heating sector. In addition, we also identified the causes of the contradiction between
1106 the energy intensity policy and the reality of the situation. Reducing energy intensity
1107 within the production process has become the core goal of environmental policy. As
1108 China was the largest consumer of fossil fuels in the world in 2011 (BP, 2012), studying
1109 the changes in energy intensity in the thermal electricity and heating sector can provide
1110 guidance for a carbon emissions reduction policy that is able to cope with the
1111 increasingly stringent energy constraints on economic development as well as the
1112 increasingly serious environmental problems. Third, the input-output structure reflects
1113 the production technology used. Thus, investigating the input-output structure effect in
1114 the thermal electricity and heating sector is conducive to measuring the contribution of
1115 the technological mitigation effect, as well as its evolutionary trend, and providing

1116 guidance for the government to tailor its energy policy accordingly. In addition, China's
1117 demand for electricity has continually increased, and the country is now facing huge
1118 fluctuations in electricity demand and a system with insufficient peak regulation
1119 capacity to cope with these. Investigating the demand structure and its impact on CO₂
1120 emissions reduction can help to predict demand for thermal electricity and heating.
1121 Doing so can inform policies designed to optimise the demand structure, improve the
1122 efficiency of electricity utilisation, and formulate electricity development plans to
1123 ensure stable electricity generation and a stable supply.

1124

1125 **6. Conclusions**

1126 In this study, we determined the key drivers of CO₂ emissions China's thermal
1127 electricity and heating sector by applying the IO-SDA method from 2007 to 2018. We
1128 also studied the evolutionary trends of these drivers, analysed the internal causes of the
1129 changes in each driver and assessed the impacts of the country's energy policy on the
1130 drivers of CO₂ emissions in the thermal electricity and heating sector. This produced
1131 four main findings:

1132 First, the growth in final demand was the main driving force behind the rise in CO₂
1133 emissions, which indicates that the swift expansion in the scale of the economy is
1134 largely responsible for increasing CO₂ emissions. Increased demand for electricity and
1135 heating in the service, and construction industries, and in heavy industries, was the main
1136 factor that explains the sharp increase in CO₂ emissions from the thermal electricity and
1137 heating sector. Moreover, the contribution of the construction industry to the final
1138 demand effect increased to a greater extent than that of heavy industry, because the
1139 country has stepped up its efforts to phase out energy-intensive, heavily polluting
1140 industries, such as steelmaking, so the demand for electricity from heavy industry has
1141 fallen. The construction industry is closely related to economic development, and
1142 infrastructure investment is also a key measure through which China is attempting to
1143 stabilise economic growth. Therefore, further reductions in energy-intensive heavy
1144 industry and increased optimisation of energy demand and electricity utilisation in the
1145 construction industry can effectively reduce carbon emissions from thermal electricity
1146 generation.

1147 Second, the emissions reduction seen in the thermal electricity and heating sector
1148 can mainly be attributed to improvements in the input-output structure. However,
1149 ongoing technological upgrading in the thermal power sector has not resulted in the
1150 desired reduction in emissions. This is because the market reform of the industrial
1151 development mechanism lags far behind the pace of technological development, and
1152 the conflict between the use of coal and the use of electricity has worsened. With the
1153 rise in coal prices, thermal electricity enterprises suffered serious losses, which led to a
1154 substantial reduction in investment and electricity generation. This led to a significant
1155 reduction in the utilisation rate of thermal electricity equipment as well as in the scale
1156 effect and the effect of technological upgrading. This implies that China needs to speed
1157 up its reform of electricity price marketisation.

1158 Third, the decrease in energy intensity was the second driving force behind the

1159 reduction in emissions during the period from 2007 to 2015. However, the overall
1160 decomposition results from 2007 to 2018 indicate that the change in energy intensity
1161 had a weak effect on increasing CO₂ emissions. In addition, we also found that the
1162 mandatory reduction in energy intensity proposed in the 11th period of the five-year plan
1163 actually had the opposite effect between 2010 and 2012. This can be largely attributed
1164 to the long-term dependence of the western region's economy on coal-based resources.
1165 The increased demand for electricity, brought about by economic growth, prompted the
1166 western region to expand its coal production and form a nascent energy base. This
1167 finding suggests that the government should have given priority to accelerating energy
1168 substitution and upgrading technology in the western region, because focusing only on
1169 reducing energy intensity could backfire. The eastern region could focus on enhancing
1170 the technological advantages and improving the technological efficiency of thermal
1171 power generation. With regard to the central region, efforts should be directed at
1172 improving thermal power generation technology, gradually phasing out small coal
1173 power enterprises, making full use of its resource advantages and improving the
1174 efficiency of its energy utilisation. Finally, the northeastern region of the country should
1175 continue to close down and/or improve small thermal power plants that are associated
1176 with high energy consumption and heavy pollution. The increment in energy intensity
1177 in 2018 implies that, during the 13th period of the five-year plan (2016-2020), it may be
1178 prove more effective to try to achieve a balance between stock adjustment and
1179 incremental optimisation in the thermal electricity sector on a regional basis.

1180 Finally, but importantly, optimising the energy structure to replace high carbon
1181 fossil energy with low carbon energy, such as blast furnace gas and converter gas in the
1182 thermal electricity and heating sector has had a sustained reduction effect, which is
1183 consistent with the policy objectives and the mainstream literature. However, the effect
1184 on reducing carbon emissions remains small, and progress still needs to be made in
1185 terms of low carbon energy and clean energy alternatives. Overall, in the process of
1186 implementing emissions reduction measures at the production end of the electricity and
1187 heating sector, it is important to strike a balance between economic development and
1188 energy consumption. In addition, when formulating energy policies, policymakers need
1189 to take full account of the reality of the situation in each province and adapt measures
1190 to local conditions.

1191 In terms of policy implications, we suggest that energy policies should be more
1192 flexible and adaptive to the varying socio-economic conditions in different cities and
1193 provinces in China. The eastern region could focus on enhancing the technological
1194 advantages and improving the technological efficiency of thermal power generation.
1195 More specifically, Tianjin, Hebei and Fujian should proactively adjust their energy
1196 consumption structure in order to reduce energy consumption and increase the
1197 proportion of new energy development and utilisation. The central region should focus
1198 more on improving thermal power generation technology, gradually phasing out small
1199 coal power enterprises, making full use of resource advantages and improving the
1200 efficiency of its energy utilisation. In addition, energy policies should guide the
1201 technological transformation and upgrade the manufacturing industry in the central
1202 region, and encourage a shift from more traditional industries to greener development.

1203 With regard to the agriculture-oriented areas in central China, the government should
1204 encourage the development of more modern forms of agriculture geared towards
1205 producing scarce, higher value products, which can then be sold for higher prices. The
1206 western region contains large provinces such as Guizhou, Shaanxi and Inner Mongolia,
1207 whose industries are largely based on coal production and fossil energy consumption,
1208 which means that it will take a longer for energy saving measures to make progress.
1209 These regions need to achieve low-carbon development through internal integration and
1210 the optimisation of coal-power-related industries. Therefore, it is necessary to
1211 concentrate equally on structural adjustment and technological progress, and in
1212 particular to improve the technological capabilities of the coal and coal-chemical
1213 industries that are associated with high energy consumption. At the same time, the
1214 promotion of energy saving technology and 'clean coal' technology in these areas is
1215 also essential. In the case of provinces with abundant wind and solar energy resources,
1216 such as Inner Mongolia, Gansu and Xinjiang, the local governments should encourage
1217 the proactive development of clean energy. Liaoning, Jilin and Heilongjiang provinces
1218 in northeastern China should continue to close down and/or improve small thermal
1219 power plants, particularly those associated with high energy consumption and heavy
1220 pollution. At the same time, they should also shut down small steel and cement
1221 enterprises. In addition, accelerating market-oriented reform in relation to electricity
1222 pricing is also important in order to realise the benefits of technology upgrading and
1223 innovation, because the moderate liberalisation of energy prices could relieve the cost
1224 pressure of thermal power enterprises, resolve the contradiction between coal and
1225 electricity to some extent, and reduce the scale effect and technology effect of thermal
1226 power enterprises. The market-oriented reform of electricity pricing should not only
1227 focus on the price per se, but should also be accompanied by adjustments in the
1228 industrial structure and the adoption of a new development pattern involving different
1229 pricing levels. For example, industries and enterprises that consume a lot of electricity
1230 and generate a high level of emissions should be forced to reduce their energy
1231 consumption by having to pay higher prices.

1232 This research has some limitations. Thermal electricity generation contributes to
1233 over a third of China's energy-related CO₂ emissions. Therefore, it is worthwhile
1234 evaluating the efficiency of thermal electricity generation and estimating its potential
1235 for reducing CO₂ emissions. Although we attempted to assess the efficiency of the
1236 production technology in our study, the findings remain sketchy. Therefore, future
1237 research could focus on constructing more comprehensive indicators with which to
1238 evaluate the efficiency of thermal electricity generation.

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