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The circular economy and carbon footprint: A systematic accounting for typical coal-fuelled power industrial parks

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ABSTRACT

Due to unclear research boundaries and a confusion between direct and indirect emissions, the impact of the circular economy (CE) on carbon emissions needs to be researched in depth. In this paper, we use a life cycle model based on carbon emissions and carbon reduction to build an emissions (reduction) matrix for the carbon footprint (CF) of coal-fuelled power generation, and then calculate the life cycle carbon emissions from China's coal-fuelled power CE parks. Results show that carbon emissions from China's coal-fuelled power at the industrial park level follow the trend of raw coal production and consumption, increasing from 2000 to a maximum of 3.25 billion tCO_2e in 2014, with the proportion of direct emissions remaining stable at above 86%. The life cycle CF in 2016 was 778.9 gCO_2/kWh, a decrease of 20.81% compared to 2000. The positive and negative impacts of the CE from 2000 to 2016 were quantitatively analysed, and resource recycling measures will reduce the overall carbon emissions of industrial parks through the substitution of carbon-intensive energy sources. Finally, policy recommendations are proposed to reduce life cycle carbon emissions by energy replacement and embodied emissions control. The novelty of this study is the quantitative evaluation of indirect carbon emissions caused by the CE and determining the correlation between CE and carbon emissions reduction.

1. Introduction

Rapid economic development, such as in China since 2000 (World Bank, 2017a), is often accompanied by energy consumption and environmental pollution. In recent years, the world has introduced paths to achieve a decoupling between economic development and resource consumption, with the circular economy (CE) being an important means of breaking through the bottleneck of resource and environmental constraints (Wang et al., 2018a). The CE can bring about the organic integration of economic development, resource conservation and environmental protection; and provide alternative value-added paths for limited resources. For example, rapid economic industrialization has caused serious environmental pollution in China, and the successful implementation of the CE is a way to “leapfrog” environmental damages (Homrich et al., 2018). The Ellen MacArthur Foundation (2017) considered the principles of the CE should extend from traditional reduction, reuse and recycling to preserving and enhancing natural capital, optimizing resource yields, and fostering system effectiveness (Ghisellini et al., 2017). Here, resource yields and system effectiveness can contribute to reducing carbon emissions, creating a distinct relationship between the CE and carbon reduction. One area where this can be seen is in industrial parks, which play an important role in economic development.

1.1. Research progress on the association of industrial parks, CE and carbon emissions

There are nearly 20,000 industrial parks globally. In the United

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States, approximately 380 industrial parks have achieved industrial agglomeration effects (Wen et al., 2016). According to the newly published "China Development Zone Audit Announcement Catalogue (2018 Edition)", there are 2543 development zones in China, among which there are approximately 130 parks with coal-powered electricity as the leading industry. These parks have played a pivotal role in the development of the CE. The "Circular Development Leading Action" released by China's National Development and Reform Commission (NDRC) requires 70% of national-level industrial parks and 50% of provincial-level parks to complete the transformation to the CE by 2020. In general, at the industrial park level, the CE concept focuses on economic growth and job creation, while at the same time reducing environmental impacts that includes carbon emissions (Smol et al., 2017).

The activities and structure of the industrial park are the main factors affecting carbon emissions. They are important carriers for industrial development, greenhouse gas emissions (GHG) and environmental pollution. Zhao et al. (2017) considered that industrial parks should take the modern manufacturing industry as the principal and green and low-carbon development as the target. Low-carbon development is a global problem, and for the global ecosystem, the overall burden matters, which is driven by human activities (Korhonen et al., 2018); and clearly, industrial parks play an important role in the carbon emissions of human activities.

Some studies assessed carbon emissions of industrial parks from different perspectives with interesting findings. For instance, Ban et al. (2016) identified that the performances of eco-industrial park projects varied according to the recycled by-products and wastes produced, and that eco-industrial park projects should work in tandem with other carbon reduction projects to reduce CO_2 emissions. Guo et al. (2018) uncovered the direct and indirect energy-related GHG emissions of 213 industrial parks from a life-cycle perspective, and found that indirect emissions accounted for 14.8% of total GHG emissions of these parks in 2015. Walmsley et al. (2018) discusses the latest industrial park developments through the lens of CO_2 footprint reduction and waste management. Meng et al. (2017) found that the main embodied GHG that dominates emissions in upstream supply chains can help focus attention on the largest emitters. In addition, there are some studies focused on how to achieve zero carbon emissions at an industrial park (Feng et al., 2018), promote low carbon pilot industrial parks in China (Yu et al., 2018), and some case studies of the Debert Air industrial park (Cote and Liu, 2016) and Suzhou industrial park (Liu et al., 2012). A lot of results have been achieved from different angles, but from a macroscopic view of the problem, the sample size of industrial parks and its statistical data is generally insufficient, leading to limitations in their research conclusions.

There is also limited research on the impacts of CE and waste treatment on carbon or GHG emissions, which includes specific types of product or waste such as plastic recycling (Liu et al., 2018), the chemical industry (Meyer et al., 2018), alkaline solid wastes (Pan et al., 2017), agricultural biomass waste (Jiang et al., 2018), and municipal solid waste (Liu et al., 2017). Zhang et al. (2016) employed panel data of 28 Chinese provinces over the period 1999–2011 to analyse the effects of industrial waste reuse on carbon emissions, and found that industrial waste reuse has a negative, direct and significant effect on carbon emissions. Further, industrial waste reuse is beneficial for economic growth. These studies demonstrated the effect of CE on carbon emissions in a particular field, but the relationship between the two has not yet become a hot topic, nor generalized for other fields.

1.2. Carbon emissions and the contribution of coal power to the CF

Countries all over the world are struggling to cope with the dual challenges of carbon reduction and energy supply (BP, 2017a). The 13th goal of the United Nations (UN) Sustainable Development Goals (SDGs) is to "Take urgent action to combat climate change and its impacts". Climate scientists have found that the concentration of CO_2 in the atmosphere has increased significantly in the past century; in particular, global emissions have increased by almost 50% since 1990 (UN, 2017). Global CO_2 emissions reached 33.44 Gt in 2017 with an average annual growth rate of 1.3% over the past decade (BP, 2017a). Although coal accounts for only 28% of the world's total primary energy consumption, it accounts for 45% of global carbon emissions because its carbon content is higher than that of other energy sources. In China, coal-based carbon emissions are the largest source of CO_2 emissions, accounting for more than 80% over the past 15 years with a peak of 85.4% in 2009 (IEA, 2017a). Therefore, the Chinese government has made it a critical issue in GHG emissions reduction in the future, and has set a goal for reducing carbon intensity by 40%–45% by 2020 and 60%–65% by 2030 (Zhao et al., 2016).

Coal-fuelled power generation plays an important role in carbon emissions. The world's annual coal production declined by 458 Mt in 2016, which is the largest decline since International Energy Agency (IEA) records began in 1971, while coal consumption fell by 1.9% in the same year (IEA, 2017b). The trend of coal in recent years seems to indicate that the prosperity of coal has become a thing of the past; however, its proportion in global energy consumption has remained above 27% for many years (BP, 2017b). Coal is the core primary energy in the power supply, and coal-fuelled power generation accounted for 38% of the world's total power generation in 2017 (BP, 2018). Demand for coal electricity in 2016 declined in countries such as China, the United States and the United Kingdom; for example, China's coal consumption fell by 1.8%–51.2 Mtce in 2016 due to the transformation of China's economic development model and greater air pollution control (BP, 2017b). Regarding power production in China, as a result of the revolution in energy production and consumption, the proportion of coal-fuelled power generation decreased from 83.3% in 2006 to 67.7% in 2016 (CEC, 2017). However, coal-fuelled power generation will continue to dominate China's power supply for the foreseeable future, and research on the carbon emissions of coal-fuelled power will continue to be a central issue in academic research.

The CF is an important method for studying carbon emissions. The CF was derived from the global warming potential and was first defined in the scientific literature in 2003 by Høgevold (2011). The CF usually stands for the amount of CO_2 and other GHGs emitted over the life cycle of a process or product, but the CF concept and its accounting method have not been uniformly defined (Čuček et al., 2012). Carbon footprint (CF) reduction tools have potential value in informing decisions, but as tools, they require capable enterprises or industry chains to be effectively employed in industry and industrial parks (Rios and Charnley, 2017). There are some studies about the carbon emissions intensity of coal-fuelled power or the CF. For example, Li and Wang (2017) used the typical CE coal-fuelled power industrial park as an example to track the carbon emission sources of an industrial park based on the life cycle method. Fang et al. (2012) calculated the CF of global electricity and found that GHG emissions from coal power generation contributed to a considerable proportion of that from the whole power sector. Meanwhile, Spath et al. (1999), Mittal et al. (2014), Odeh et al. (2008), Mallia and Lewis (2013), Messagie et al. (2014), and Santoyo-Castelazo et al. (2011) studied the carbon emissions of electricity sector in the United States, India, the United Kingdom, Canada, Belgium and Mexico, respectively. Notably, Liao et al. (2013) calculated that the CF of China's coal-fuelled power generation was 892 gCO_2e/kWh in 2010, which differs greatly from the 707 gCO_2e/kWh calculated by the World Bank (2017b). In addition, carbon emissions generated from coal in China in 2015 were estimated by some international organizations such as the IEA (2017a) (7405 Mt) and the U.S. Energy Information Administration (EIA, 2017) (6913 Mt), with apparent differences in results.

1.3. Progress in carbon footprint, circular economy and their relationship

Two problems can be found from the above analysis. First is the inconsistency in research boundaries and methods for calculating CF. Second is in the progress, or lack of research, on the relationship between the CE and the CF?

(1) The reason for the different results in CF research may come from technological differences, and thus specific emissions, between countries. The difference in results for the same country may be due to differences in accounting boundary and methods. First, none of the studies above distinguished between direct emissions and implied emissions within the CE framework; in particular, they ignored emissions from coal production and post-mining activities. Second, there are differences in accounting methods. Some studies (such as Fang et al., 2012; Odeh and Cockerill, 2008) merely focus on power generation instead of life cycle assessment (LCA) methods or use LCA methods from the perspective of "power plant construction-operation-disposal" rather than "coal production-coal washing-power generation". Third, there is a difference in data acquisition channels, such as the accuracy of data on power consumption related to raw coal washing, and a distinction between underground mining and surface mining (Ditsele and Awuah-Offei, 2012).

(2) There have been many studies on CE industrial parks or low-carbon industrial parks. Further, symbiosis and eco-parks are identified as two main clusters within the CE field. There is also an outstanding connection between the CE and China owing to the number of publications about Chinese cases, which are mostly related to industrial ecology and eco-industrial parks. In addition, general publications on the CE mostly come from China-related cases since the mandatory CE regulation was enforced in 2009 (Homrich et al., 2018). Nevertheless, the impact of the CE on carbon emissions, an aspect of the breakthrough to sustainability, is seldom discussed in the CE or carbon emissions literature. This situation is reflected in the study by Geng et al. (2012): Carbon reduction indicators are not incorporated into the CE evaluation indicator system at the industrial park level. Additionally, in the study by Homrich et al. (2018) identifying hot topics or debates related to studies on the CE, initially a search was performed on the selected sample of 327 articles by using bibliometric analysis, and the authors found that the "carbon emissions" issue is not yet a hot topic within the CE. The reason for this omission is that the Department for Climate Change Response of the NDRC initiated a "low-carbon economic development" project in 2010, where CO_2-related indicators have been used separately to evaluate carbon reduction performance.

In summary, research on the impact of the CE on the carbon emissions of industrial parks is insufficient. For example, is there a positive or negative impact of the CE on CF at the industrial park level? What is its quantitative impact? How can carbon emissions be better controlled through the development of the CE? This paper conducts an in-depth analysis through the LCA method. Due to the wide range of applications of electricity, research on coal-fuelled power generation from the cradle-to-cradle perspective is difficult. Therefore, this study chooses cradle-to-gate assessment, which is a partial product LCA from resource extraction (cradle) to the factory gate. To that end, the LCA measurement model (cradle-to-gate) contains direct emissions (on-site, internal) and indirect emissions (off-site, external, and embodied) (Wiedmann et al., 2010). In Section 2, this paper first defines the life cycle boundary of CE coal-fuelled power industrial parks and divides the entire process into four stages: coal mining, raw coal processing/washing, coal-fuelled power generation, and comprehensive utilization. Then the general model of coal-fuelled power carbon emissions is designed, and the accounting methods for each stage are determined separately, with the uncertainty analysis model of the system also being developed. Section 3 is an empirical study based on the above four stages, and it extends from the park scale to the national scale. We analyse the structure and trends of China's carbon emissions from coal-fuelled power parks from 2000 to 2016, quantitatively evaluating the positive and negative impacts of the CE on CF of coal-powered industrial parks. Section 4 calculates the total carbon emissions and CF of CE coal-fuelled power industrial parks and evaluates the overall impact of the CE on carbon emissions. Finally, Section 5 provides LCA-based carbon emissions reduction countermeasures for coal-fuelled power industrial parks.

2. Model

2.1. Boundaries and hypothesis

System boundaries are a prerequisite for the accuracy and comparability of accounting. However, there are significant inconsistencies in the system boundaries of existing studies on coal-electricity CF. For example, Steinmann et al. (2014) include coal extraction, transport and power generation. Wang et al. (2012) believe that additionally, coal mining and processing, power generation of coal gangue, and coalbed methane should also be included. The study by Shen et al. (2014) includes power generation, coal mining, coal processing and transportation. While these studies include most aspects of the coal-fuelled life cycle, they ignore fugitive carbon emissions from post-mining activities. In a recent policy document (GAQS, 2017) released in China, the boundary includes coal mining, raw coal processing, methane recycling, fugitive mining emissions, and methane escape emissions post-mining. This boundary is presently the most comprehensive, but it still ignores fugitive emissions of CO_2 as well as emissions and emissions reductions caused by the resource recycling stage.

Typical coal-fuelled power generation usually consists of the following industry chain: coal production - coal processing – transportation - power generation - resource recycling (Wang et al., 2018b). Further, we divide the carbon emissions of a CE coal-fuelled power industrial park into four stages (see Fig. 1): coal production, coal processing and fugitive emissions, power generation, and resource recycling. These stages cover traditional accounting content and take into account fugitive emissions of CO_2 and methane, as well as coal gangue utilization to conduct more comprehensive accounting of carbon emissions in coal-fuelled power parks. Notably, the transportation stage is usually included at the macro level of LCA. In 2016, China's average cargo transportation distance was 425.4 km (NBS, 2018), with considerable corresponding carbon emissions. However, at the level of the CE coal-fuelled power industrial park, there is no long-distance transportation, and energy consumption is very small; thus, carbon emissions from this stage are usually not included in the accounting. Due to discrete carbon emissions data for coal-fuelled power parks, and to facilitate calculation, the park scale is expanded to a national-scale virtual park for accounting.

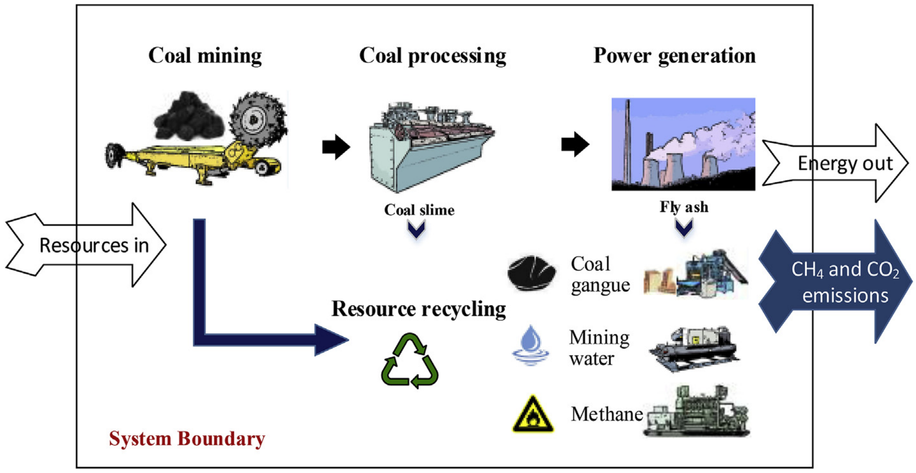

Fig. 1. Boundary of coal-fuelled power industrial parks in LCA.

The drivers for carbon emissions and emissions reduction for the four stages are shown in Table 1. According to Wiedmann et al. (2010), direct emission is defined as emissions from power generation, and indirect carbon emission are from coal production, coal processing and fugitive emissions, and resource recycling. In this study, coal mining is set in terms of underground mining due to the fact that most of China's coalmines are underground. The coal used for power generation generally undergoes a washing process; the processing rate of raw coal in China reached 70% in 2017. Resource recycling includes coal gangue utilization (for power generation and building materials), methane power generation, and heat utilization from mining water, with methane control and utilization (100 million m^3) and mining water energy recovery (10,000 tce) constituting two emissions reduction measures.

The conversion factor during the carbon evaluation will affect the results of the study. The emissions coefficient of coal-fuelled power was 2.62 tCO_2/tce in the China First Biennial Update Report on Climate Change (NDRC, 2016), but the latest study by Liu et al. (2015) considers a factor of 1.8003 tCO_2/tce. These findings are the two most important research results, and their average (2.21 CO_2/tce) is chosen as the conversion factor, with a level of uncertainty of ±22.8%. Another important factor is the GWP of CH_4. According to the Intergovernmental Panel on Climate Change (IPCC) (2007) AR2 and AR4 reports, the GWP of methane is 21 and 25, respectively. The average value, 23, is used in this paper; that is, one ton of methane is equivalent to 23 tons of CO_2, and 10,000 m^3 of methane is equivalent to 154.1 tons of CO_2 equivalent, with a level of uncertainty of ±8.7% (±2/23).

2.2. Accounting model

There are some accounting models for carbon emissions; for example, IPCC Tier 1 is commonly used, where carbon emissions are defined as the product of energy consumption and emissions factors. In addition, the U.S. Environmental Protection Agency (EPA) defines carbon emissions as $E = A \times EF \times (1 - ER/100)$, where E is total emissions in units of pollutant per unit of time; A is the activity rate in units of weight, volume, or duration per unit of time; EF is the emissions factor in units of pollutant per unit of weight, volume, or duration; and ER is the overall emissions reduction efficiency as a %. Observably, the emissions factor is one of the key indicators in studies. Liu et al. (2015) found that the level of uncertainty of the carbon emissions of China's fossil energy combustion in 2008 reached 15% due to the error of emissions factors, leading to three results concerning CO_2 emissions factors for coal: 2.6143 t CO_2/t coal (IPCC, 2006), 1.9003 t CO_2/t coal (NDRC, 2011), and 1.8003 t CO_2/t coal (Liu et al., 2015).

To avoid the errors caused by these research results, and based on the LCA of coal-fuelled power parks, this study starts from the input energy consumption, fugitive emissions, coal conversion emissions, and emissions reduction of resource recycling. Then, the net emissions of the system covering the four stages are constructed in the following accounting model:

$$E = \sum_{s=1}^{4} E_s = \sum_{s=1}^{4} (InputE_s + FugitiveE_s + ConversionE_s - EmissionR_s) \quad (1)$$

where $InputE_s$, $FugitiveE_s$, and $ConversionE_s$ are input energy emissions, fugitive emissions and coal conversion emissions, respectively, and $EmissionR_s$ is the indirect emissions reduction of methane and coal mining water.

Finally, the CF of a coal-fuelled power park can be calculated as follows:

Table 1
Drivers of life cycle carbon emissions of the four stages.

Stage	Emissions (reduction)	Drivers
Coal production	CH_4 and CO_2 emissions	Raw coal production (Mt), energy consumption of raw coal production (kgce/t), CH_4 and CO_2 (fugitive) emissions from coal production ($MtCO_2e$)
Coal processing and fugitive carbon	CH_4 and CO_2 emissions	Amount of raw coal washed (Mt), energy consumption of coal washing (tce), amount of gangue washed and slime (Mt), fugitive CH_4 and CO_2 ($MtCO_2e$)
Power generation	CO_2 emissions	Coal-fuelled power generation (MkWh), standard coal consumption of the power supply (g/kWh)
Resource recycling	CH_4 and CO_2 emissions reduction, CO_2 emissions	Gangue used for power and building materials (Mt), coal gangue power generation (MkWh), methane utilization (Mm^3), energy recovery of mining water (tce)

$$CF = \frac{E}{CFP\ generation} \quad (2)$$

where CF is the carbon footprint of coal-fuelled power generation (gCO_2e/kWh), E is total carbon emissions over the life cycle of power generation (tCO_2e), and CFP generation is the total coal-fuelled power generation in coal-fuelled power parks (MkWh).

The four types of emission/reduction matrices corresponding to the above four stages are shown in Table 2, and the detailed decomposition studies are as follows:

2.2.1. Coal production

In general, coal production is divided into open-pit mining and underground mining. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories define three sources of emissions from coal mining activities: underground mining, open-pit mining and post-mining activities; furthermore, "Related agencies should choose a methane emissions factor range of 10–25 m^3/t and should consider country-specific variables". In China, underground mining is a dominant mining method, and the carbon emissions of coal production include three aspects: First, the carbon emissions from energy consumption for coal production processes such as the electricity used for ventilation, coal lifting, and water drainage ($InputE_1$); second, methane and CO_2 emissions during coal production ($FugitiveE_1$); and, third, spontaneous emissions from combustion of stacked raw coal and coal gangue. However, this last aspect can be controlled under current technical conditions, and including it in the study's boundary is unnecessary. According to formula (1), the calculation method of coal production emissions can be expressed as follows: $E_1 = InputE_1 + FugitiveE_1$. The coefficient for methane emissions in this stage is 9.176 m^3 per ton of raw coal (Wang et al., 2015). The IPCC and related studies do not give the emissions coefficient of fugitive CO_2; thus, we simulated the statistics of some mining companies (e.g., Xuzhou Mining Group and Lu'an Mining Group) and calculated relative emissions of CO_2 in 2010 as 4.73 m^3/t coal, with a level of uncertainty of 10%.

2.2.2. Coal processing and fugitive carbon emissions

Coal processing/washing has become the choice of most coal mines in China. According to China Coal Processing and Utilization Association (CCPUA) statistics on the coal industry, the raw coal processing rate reached 70% in 2017. The carbon emissions of coal processing are mainly derived from two factors: first, the energy consumption during the coal washing process, mainly for coal washing equipment ($InputE_2$); and, second, the methane and CO_2 fugitive emissions during the washing process or post-mining activities ($FugitiveE_2$). Coal processing will reduce the transportation volume of coal gangue; however, these carbon emissions are negligible in industrial parks because there is no long-distance transportation. Therefore, the formula for carbon emissions from coal processing is expressed as follows: $E_2 = InputE_2 + FugitiveE_2$. Notably, coal processing can increase the energy efficiency of coal-fuelled power generation, but it has little effect on the carbon emissions from coal-fuelled power generation.

Emissions from post-mining activities includes fugitive methane and CO_2. The IPCC noted that the post-mining activities coefficient of coal mine methane is in the range of 0.9–4 m^3/t coal globally. However, in China, according to the General Administration of Quality Supervision, Inspection and Quarantine (GAQS, 2017), the methane emissions factors of gas outburst from and high gas mines should use a default value of 3 m^3/t, and that from other low gas mines should use a value of 0.94 m^3/t. Wang et al. (2015) found that the proportion of these three types of mines in 2010 was 10.55%, 23.51% and 67.34%, respectively. Thus, after weighting the calculation, the emissions factor of post-mining activities is 1.655 m^3 CH_4 per ton of raw coal. Currently, there are no authoritative data on the fugitive emissions of CO_2. The proportion of fugitive CO_2 and CH_4 is supposed to have the same ratio, and after multiplying by the emissions of CH_4 ($1.655/9.176 \times 4.73$), the factor of fugitive CO_2 is 0.85 m^3 CO_2e/t coal in 2010, with a level of uncertainty of 5% for the data on the two types of fugitive emissions.

2.2.3. Power generation

Power generation is the main stage for carbon emissions in the park. Carbon emissions are mainly caused by the energy conversion of coal combustion ($ConversionE_3$), and emissions from the self-use energy of power plants ($InputE_3$). The total emissions from coal-fuelled power generation can be expressed as follows: $E_3 = InputE_3 + ConversionE_3$. One kilogram of carbon is completely burned to produce 3.67 kg of CO_2 (44/12). The data on coal-fuelled power generation comes from the statistical report by the China Electricity Council.

2.2.4. Resource recycling

Many coal-fuelled power parks in China have resource recycling measures, mainly involving methane power generation, coal gangue/slime for power generation and building materials, and the use of mining water. Some parks adopt new measures such as solar power generation in the subsidence area, but this measure is not a common practice and is not considered in this research. Coal gangue combustion can increase CO_2 emissions ($ConversionE_4$). According to CCPUA industry statistics, coal gangue emissions in China in 2017 reached 672 million tons, and the comprehensive utilization of coal gangue reached 452 million tons. As a GHG with high global warming potential, methane has been used in many mining areas to generate electricity, which greatly reduces carbon emissions ($EmissionR_4$). In 2017, China's coalbed methane extraction capacity was 17.77 billion cubic metres (including underground extraction and surface drainage), of which the underground gas extraction volume was 12.81 billion cubic metres for a utilization rate of 38.2%. The surface gas drainage volume was 4.96 billion cubic metres for a utilization rate of 88.7%. The utilization of mining water for heat pumps can indirectly reduce carbon emissions ($EmissionR_4$), although the amount of mining water used as a water source heat pump is small, it has better development prospects because China's mining water utilization in 2017 was approximately 3.85 billion tons, for a utilization rate of approximately 72%. Therefore, the carbon emissions in this stage can be expressed as follows: $E_4 = ConversionE_4 - EmissionR_4$. The levels of uncertainty in the data on gas power generation, coal gangue utilization and mining water are estimated to be 10%, 10% and 30%, respectively.

Table 2
Coal-fuelled power carbon emissions matrix for coal-fuelled power industrial parks.

	$InputE_s$	$FugitiveE_s$	$ConversionE_s$	$EmissionR_s$
Coal production (E_1)	✓	✓		
Coal processing and fugitive carbon (E_2)	✓	✓		
Power generation (E_3)	✓		✓	
Resource recycling (E_4)			✓	✓

2.3. Uncertainty analysis

An uncertainty analysis was conducted to determine the impact of the estimated data and variations in the data on the conclusions. Each parameter was changed independently of all others so that the magnitude of its effect on the base case could be assessed (Spath et al., 1999). In some cases, an increase in uncertainty may occur for one inventory development method versus another because each method has different data requirements. For example, aggregate estimates of emissions are sometimes more accurate because they are based on or can be compared to easily measured values, whereas disaggregated estimates may require additional assumptions for which data or the capability to verify estimates is not as readily available (IPCC, 2007). As mentioned above, there are some uncertainties in the conversion coefficients, carbon emissions and other data. To analyse the reliability of the system, two methods for combining uncertainty analysis are used. The first is an addition and subtraction error transfer formula, and the second is the multiplication error transfer formula.

(1) Addition and subtraction error transfer formula:

$$U_c = \frac{\sqrt{(U_{s1} \times \mu_{s1})^2 + (U_{s2} \times \mu_{s2})^2 + \ldots + (U_{sn} \times \mu_{sn})^2}}{|\mu_{s1} + \mu_{s2} + \ldots + \mu_{sn}|} = \frac{\sqrt{\sum_{i=1}^{n} (U_{si} \times \mu_{si})^2}}{\left|\sum_{i=1}^{n} \mu_{si}\right|} \quad (3)$$

where U_c is the combined uncertainty of n parameters (%), U_{s1} … U_{sn} are the separate uncertainty levels of n parameters (%), and μ_{s1} … μ_{sn} are the values of n parameters.

(2) Multiplication and division error transfer formula:

$$U_c = \sqrt{U_{s1}^2 + U_{s2}^2 + \ldots + U_{sn}^2} = \sqrt{\sum_{i=1}^{n} U_{si}^2} \quad (4)$$

where U_c is the combined uncertainty of n parameters (%) and U_{s1} … U_{sn} are the separate uncertainty levels of n parameters (%).

3. Empirical study

Based on the models and using coal-fuelled electricity data, we quantitatively analyse the carbon emissions and emissions factors of the four stages in China from 2000 to 2016. In addition to annotations in the text, all of the data sources are listed in the Supplementary information section.

3.1. Coal production

China's raw coal production has grown rapidly with economic development, increasing from 1.384 billion tons in 2000 to 3.969 billion tons in 2013 and then slightly decreasing to 3.41 billion tons in 2016. With the fluctuation in yield of raw coal, total CO_2 emissions from the energy consumption of coal production first increased and then decreased. Fugitive carbon emissions in the production stage also had the same trend. As shown in Fig. 2, the total carbon emissions from coal production (including energy consumption emissions, CH_4 fugitive emissions, and CO_2 fugitive emissions) were only 261.8 $MtCO_2e$ in 2000, and with the changes in raw coal production, it soared to a high of 648.85 $MtCO_2e$ in 2013. It then fell to 519.78 $MtCO_2e$ in 2016.

Carbon emissions factors in the coal production stage have shown a fluctuating trend, starting at 189.2 $kgCO_2e$/t coal in 2000, decreasing to 187.0 $kgCO_2e$/t coal in 2009, and beginning to significantly drop to the lowest value of 145.9 $kgCO_2e$/t coal in 2015. This result is mainly due to the improvement in coal mining technology and the attention of decision-makers to low-carbon management, leading to energy efficiency improvements in equipment motors (in ventilation, lifting, drainage, etc.) that have reduced GHG emissions. The growth rate of GHG emissions is lower than that of raw coal production.

3.2. Coal processing and fugitive carbon emissions

The amount of coal processing/washing in China rose from 0.337 billion tons in 2000 to 2.469 billion tons in 2014, increasing by nearly 600% in 15 years. Since then, it decreased only slightly to 2.349 billion tons by 2016. The main means of coal washing include jigging coal preparation and heavy medium coal preparation; all of these processes require electricity-based energy use, which inevitably produces carbon emissions. As the coal production and raw coal processing amount has steadily been increasing since 2000, the total amount of carbon emissions from coal processing and fugitive emissions first increased and then decreased, as shown in Fig. 3. In 2013, it reached a maximum value of 122.3 $MtCO_2e$, of which coal processing accounted for 16.92 $MtCO_2e$. Post-mining fugitive carbon has a close positive relationship with coal production, and the highest value was 105.41 $MtCO_2e$ in 2013, of which fugitive CH_4 accounted for approximately 94%.

The carbon emissions factor shows a downward tendency, falling from 45.7 $kgCO_2e$/t coal in 2010 to 31.1 $kgCO_2e$/t coal in 2016, a decline of 31.8% and indicating that carbon emissions from this stage have been satisfactorily controlled. This beneficial result is mainly owing to two factors. First, technological progress has reduced marginal power consumption. Thus, the electricity consumed per ton of raw coal declined year over year. Second, the fugitive emissions coefficient for post-mining activities also tended to decline due to the increased use of methane extraction in many mining areas such as Guizhou and Shanxi provinces.

3.3. Power generation

China's coal-fuelled power generation increased from 1060 billion kWh in 2000 to a maximum of 4026.6 billion kWh in 2014 and then dropped slightly to 3905.8 billion kWh in 2016. Following the same trend, total carbon emissions of power generation increased to the highest value of 2838.7 $MtCO_2e$ in 2014 and then decreased slightly until 2016 (Fig. 4).

The carbon emissions factor of coal-fuelled power generation is closely related to the power generation and the coal consumption of the power supply. With the upgrades in China's coal-fuelled power technologies in recent years, the amount of coal used for power supply has been decreasing every year, from 392 gce/kWh in 2000 to 312 gce/kWh in 2016. The emissions factor is also showing a declining trend, dropping from 866.3 gCO_2e/kWh in 2000 to 689.5 gCO_2e/kWh in 2016, a decrease of 20.4%.

3.4. Resource recycling

Resource recycling is a key part of CE development in coal-fuelled power industrial parks. With the increasing emphasis on the development of the CE in China from 2000 to 2016, the utilization of coal gangue (sludge), mining water and coal methane increased by 6.8, 16.3, and 14.8 times respectively. As mentioned above, the CE has positive and negative effects on carbon emissions, and coal gangue will lead to an increase in carbon, which is a reflection of the negative effects of the CE. In the resource recycling

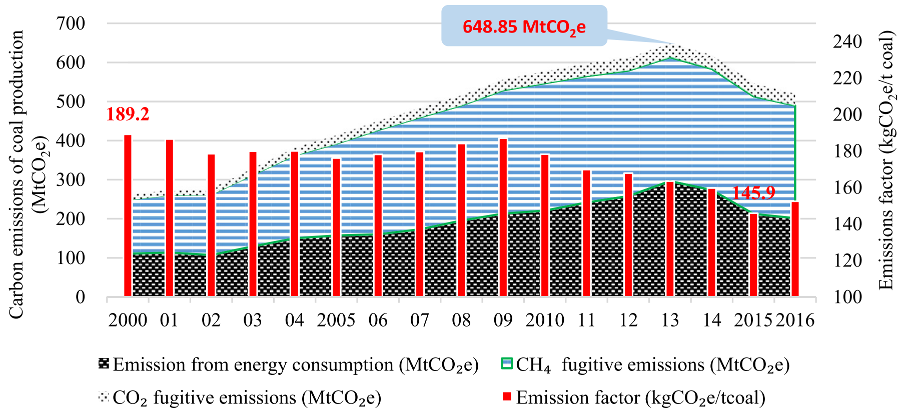

Fig. 2. Carbon emissions structure, factors and trends of coal production.

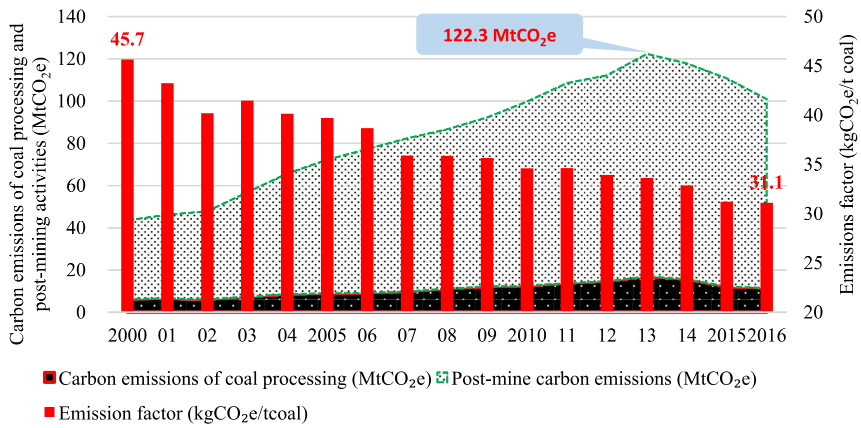

Fig. 3. Carbon emissions structure, factors and trends of coal processing.

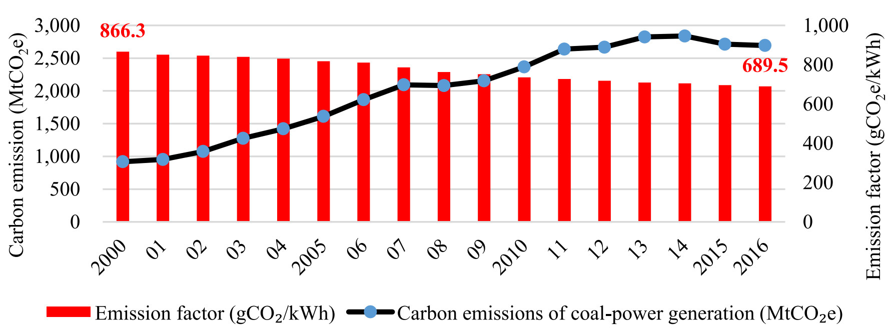

Fig. 4. Carbon emissions factors and trends of coal-fuelled power generation.

stage, carbon emissions are dominated by coal gangue utilization, and gangue utilization has increased steadily since 2000, indicating that the comprehensive utilization of coal gangue has received more attention in the industry. In 2014, gangue emitted a maximum of 116.48 $MtCO_2e$, of which the proportion of gangue power generation was above 75%. Since the cost of gangue building materials (especially bricks) is higher than that of clay bricks, and the production of gangue brick is unstable, the amount of carbon emissions from building materials has decreased in recent years, accounting for only approximately 2% in 2016. However, with technical improvements and cost reductions, it is possible that the use of gangue building materials will recover in the future. Notably, although coal gangue utilization has increased carbon emissions, it is of great significance for energy conservation and environmental pollution reduction.

The reduction in carbon (positive effects) from CE coal-fuelled power industrial parks is mainly reflected in the comprehensive utilization of methane and mining water. The rate of carbon reduction increased 17-fold, from 5.584 $MtCO_2e$ in 2000 to 96.664 $MtCO_2e$ in 2016, showing a significantly upward trend. As shown in

Fig. 5, accompanied by the reduction in gangue emissions, methane and mining water utilization have helped the emissions factor of resource recycling fall from its peak value in 2014 to the 2000 level of only 3.9 kgCO_2e/t coal.

4. Results and discussion

4.1. Total emissions and carbon footprint

4.1.1. Total emissions initially increased and then decreased

As shown in Fig. 6, there was an increase in coal-fuelled life cycle carbon emissions between 2000 and 2014, followed by a slight decrease to 2016, the same trend as that of China's raw coal production and consumption. In 2014, total emissions reached a maximum of 3250 MtCO_2e, with the proportion of emissions from power generation above 86% and constituting the dominant contributor. Indirect carbon emissions from other stages account for 10–14% of life cycle emissions, with coal production making a major contribution. The proportion of indirect carbon emissions does not follow a specific trend in the time series. Further, it is lower than research results by Guo et al. (2018) that shows indirect carbon emissions account for 14.8% of total GHG emissions in 2015. This suggests that indirect carbon emissions of coal-fuelled power industrial parks is just merely better than the average for Chinese national-level industrial parks.

The CE of coal-fuelled power parks is mainly reflected in coal processing and comprehensive resource utilization. The carbon emissions from these two parts have stabilized at above 80 MtCO_2e since 2011, exceeding 100 MtCO_2e after 2013. These emissions are ignored in most previous studies, leading to an underestimation of the life cycle carbon emissions of coal-fuelled power generation.

4.1.2. Comparison of the carbon footprint

Different from previous studies, which focused on direct emissions from power plants while excluding other aspects in the whole industrial process, by analysing life cycle carbon emissions, this paper found that the CF of the whole process is 13% higher than that of power generation. In Fig. 7, the emissions factor of coal-fuelled power generation in power plants (direct emissions) dropped from 866.3 gCO_2/kWh in 2000 to 689.5 gCO_2/kWh in 2016, a decrease of 20.41%. The life cycle CF decreased by an even higher percentage, 20.81% from 983.6 to 778.9 gCO_2/kWh over the same period, mainly due to the contribution of energy savings and emissions reductions in the CE stages.

In this study, the life cycle CF of coal-fuelled power parks in 2016 was 779 gCO_2e/kWh. At present, it is difficult to compare this finding with other results due to a lack of literature on the CF of industrial parks. However, from the perspective of a single stage, the CF of coal-fuelled power plants can be compared with other research results. In 2009, direct emissions of coal-fuelled power in this paper was found to be 751 gCO_2e/kWh, which is lower than comparable results by Liao et al. (2013) (892) and Qi (2011) (866.3). The main reason for this discrepancy is that the coal-to-electricity conversion factor was different. We used the average of the values from the NDRC (2016) and Liu et al. (2015), while the other two studies used the value provided by the NDRC (2016) (2.62). In other words, the emissions factor may directly impact results of the assessment (usually overestimated in the past) for total emissions.

4.2. The impact of CE on carbon emissions

This study found that in industrial parks, there is a dual effect of the CE on the CF: positive (carbon reduction) and negative (carbon emissions). As Table 3 shows, positive effects are attributable to methane and mining water utilization, which reduced the CF by 11.4 gCO_2e/kWh in 2016. This finding is similar to the conclusion of Ban et al. (2016) and Zhang et al. (2016), which found that industrial waste reuse is beneficial for carbon emissions reduction, and promoted the linkage between industrial park projects and CO_2 emissions reductions. The negative effect is mainly attributable to coal processing and gangue utilization, with the net CF increasing by 20.8 gCO_2e/kWh in 2016. Taken together, CE measures such as raw coal processing and resource recycling in coal-fuelled power parks have generally increased the life cycle CF (9.4 gCO_2e/kWh in 2016). From 2000 to 2016, the increase in carbon emissions caused by the CE was approximately 1098 MtCO_2e. This finding indicates that on the surface, the CE has an overall increasing effect on the CF of coal-fuelled power generation. However, from the perspective of the entire energy system, and accounting for inevitable emissions from energy substitution (coal gangue power is a substitute for coal power, for example), the CE has actually reduced carbon emissions. From 2000 to 2016, the development of the CE is estimated to have reduced carbon emissions (through methane and mining water utilization) by approximately 250.4 MtCO_2e. For instance, although coal gangue utilization increases carbon emissions, in the process of coal gangue power generation and building materials, the energy

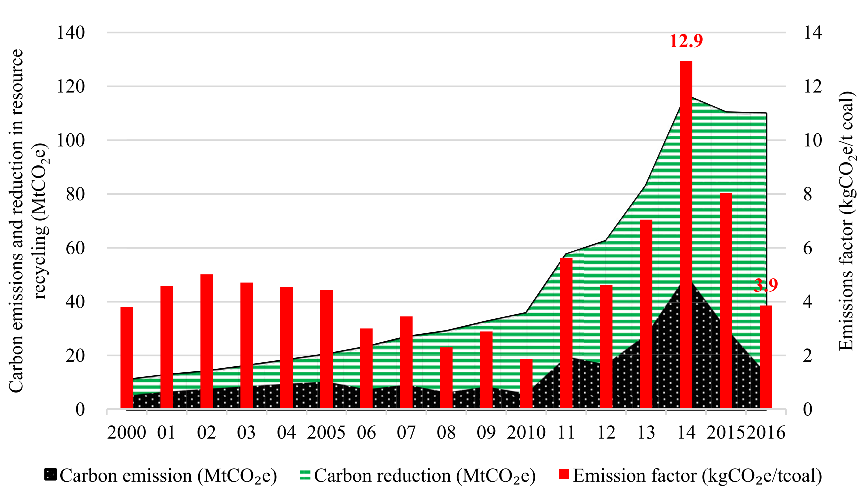

Fig. 5. Carbon emissions structure, factors and trends of resource recycling.

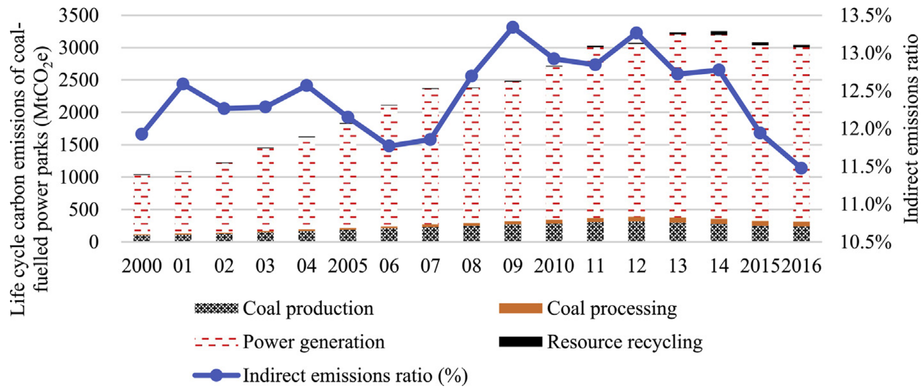

Fig. 6. Time series trend of life cycle carbon emissions in coal-fuelled power parks.

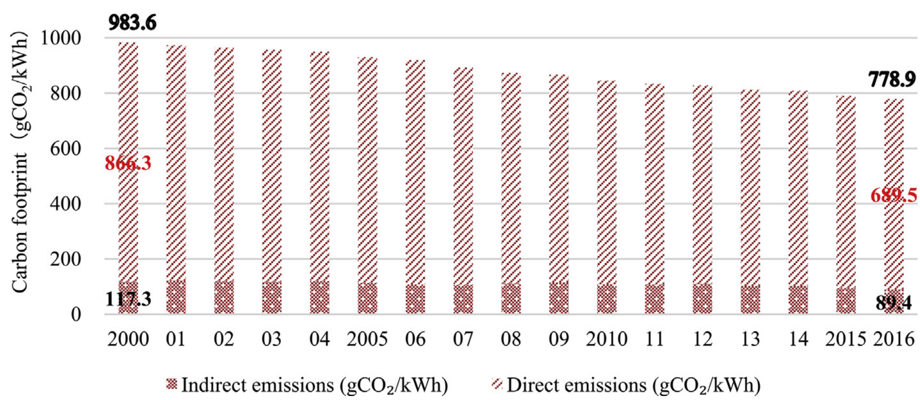

Fig. 7. Comparative analysis of the coal-fuelled power generation CF.

Table 3
Impact of CE development on the CF in coal-fuelled power parks (unit: gCO_2/kWh).

	Coal production	Coal processing	Resource recycling			Indirect emissions	Direct emissions	Carbon footprint
			Emissions	Emissions reduction	Net increase			
2001	101.4	15.4	7.9	2.2	5.7	122.5	850.9	973.4
2006	91.2	13.1	7.0	3.1	3.9	108.2	811.1	919.3
2011	84.3	17.1	11.1	5.3	5.8	107.2	727.1	834.2
2016	61.2	18.7	20.8	11.4	9.4	89.4	689.5	778.9

generated by gangue substitutes energy generated by coal, having little comprehensive impact on carbon emissions of the entire system.

Therefore, just like the European Union, China still attaches great importance to the development of the CE, mainly for the following reasons: (1) Improving energy efficiency. As a primary energy source, high-grade coal can be used properly, while large amounts of low-grade resources are wasted in the cases of coal gangue, slime and methane, which are discarded. The CE considers these wastes to be misplaced resources and uses them through technological advances. (2) Reducing environmental pollution. If coal gangue is not properly used, then it will often cause spontaneous combustion after being stockpiled, and pollutants such as SO_2 and NOx will be emitted into the atmosphere, or pollutants such as heavy metals will flow with rainwater into the land and cause soil or water pollution. If methane is not used, it will be emitted into the atmosphere and constitute further carbon emissions. In addition, from the perspective of carbon emissions reduction: (3) Reducing the opportunity cost of emissions. In 2016 alone, the emissions reduction from methane and mining water utilization reached 44.5 $MtCO_2e$, indicating that carbon emissions have been greatly reduced through the CE. With the increase in methane utilization, the CE may reduce the total amount of carbon emissions in the foreseeable future.

4.3. Systematic uncertainty analysis

There is some uncertainty in this research that can be summarized in the following three ways: First, some parameters are inconsistent, especially with respect to the level of uncertainty of the emissions factors. Second, the sample size or statistical data are insufficient or lacking. For example, there is no measurement method of post-mining activity CO_2 emissions, and mining water heat pump data are very difficult to obtain under existing conditions. Third, regarding the variability in coal-fuelled power plant efficiency (Steinmann et al., 2014), similar alternative data are used based on methods of interpolation or extrapolation.

According to formula (3) and formula (4), the systematic uncertainty of life cycle carbon emissions is ±17.92% (as shown in Table 4), and the main contributor is the emissions factor of power

Table 4
Systematic uncertainty of life cycle carbon emissions (2016).

Stages	Uncertainty (U_{si})	Uncertainty (U_{si}) excluding the conversion factor	Value (μ_{si})-MtCO_2e
Coal exploitation	10.1%	10.1%	519.78
Coal washing and post-mining activities	8.3%	8.3%	100.96
CFP generation	22.8%	0.0%	2693.13
Resource reuse	4.7%	3.5%	125.81
U_c	17.92%	1.55%	–

generation. If the coefficient of coal to CO_2 (2.62 tCO_2/tce in NDRC (2016)) is removed, then the systematic uncertainty falls to ±1.55%.

In spite of this uncertainty, we believe that our CF estimate is more accurate than that in the past studies for the following reasons:

First, we use a more reasonable system boundary in this study. Previous studies such as those by Liao et al. (2013) and Qi (2011) studied only the emissions from coal-fuelled power generation and did not consider emissions for the entire process. Messagie et al. (2014) used LCA but omitted the fugitive emissions from post-mining activities, which should not be ignored. Differently, this article covers all four important stages of CE coal-fuelled power industrial parks.

Second, we ensure the accuracy of the parameters. Past studies using LCA have some drawbacks in calculation and uncertainty. For instance, the studies by Wang et al. (2012) and Shen et al. (2014) provided a rough estimate, ignoring the accuracy of key parameters. They considered the electricity consumed by coal washing to be 3 kWh/t coal, which is far below the actual level of that time, which reached up to 5 kWh/t coal for advanced technologies (MEP, 2008). Instead, this study uses much more practical values: 5.51 kWh/t coal in 2010 and 4.80 kWh/t coal in 2016, which were calculated from industry statistics.

Third, we use more accurate data sources. This study uses statistical data from authoritative bodies such as the National Bureau of Statistics (NBS) and the CEC. Data that are unavailable in the literature such as the raw coal washing capacity and mining water reuse are substituted by coal industry statistics from industrial associations. Such statistics, which are also lacking in other studies, are the most realistic data that can be found to date.

4.4. *Life cycle-based policy initiatives*

The Chinese government regards low-carbon development as a strategy for economic development and for building an ecological civilization. In the past policy framework, practices for controlling carbon emissions paid more attention to adjusting the industrial structure, improving energy efficiency, optimizing the energy structure and increasing carbon sinks. These measures have played an important role in the macro reduction in carbon from coal-fuelled power parks. In addition, according to the findings in this paper, other policy measures should be promoted in the following ways:

(1) Increase the substitution of coal power. Coal combustion accounts for more than 86% of life cycle emissions of coal-fuelled power generation; thus, from the perspective of the whole process, carrying out a coal-fuelled electricity generation substitution and accelerating the replacement of renewable energy (especially hydropower, wind power, and photovoltaic power generation) should be the main means of controlling overall carbon emissions. A report by BP (2017a) suggests that as coal is replaced by lower-carbon energy, the share of China's coal demand will fall from approximately two-thirds in 2015 to less than 45% in 2035. As China's economy continues to develop steadily and electricity consumption continues to increase, energy substitution is the most important measure to reduce carbon emissions in the coal-fuelled power industry.

(2) Control indirect carbon emissions. As a hidden factor of the life cycle carbon emissions of coal-fuelled power generation, the CE has two effects. First, it increases direct carbon emissions, mainly CO_2 emissions from coal gangue utilization, and hidden fugitive carbon during and after mining. However, it does not increase overall emissions from the whole energy system perspective. Second, the CE has a carbon reduction effect, mainly due to the comprehensive use of resources such as methane and mining water. CE-relevant policies should be oriented towards reducing implicit emissions. For example, encouraging coal-electricity joint ventures that force coal to be used locally, reducing fugitive carbon emissions; continuing to strengthen waste utilization such as methane and mining water; and further reduce carbon emissions while treating wastewater (Sepehri and Sarrafzadeh, 2018).

(3) Strengthen life cycle emissions monitoring. Low-carbon technology joint systems for coal, power and resource recycling companies in the industry chain should be developed. The role of big data in carbon emissions monitoring prediction and early warning should be highlighted, and carbon emissions data collection in all industry links of parks should be strengthened. Data traceability should be fully used to analyse carbon emissions networks, and the ability to monitor and forecast the carbon emissions in industrial network operations should be improved.

(4) Actively tap technology and market potential. The promotion of low-carbon technologies and the construction of carbon emissions technology systems for coal, electric power and resource recycling enterprises should be strengthened, especially for low-carbon technology in the deep use of methane and coal gangue. A GHG data life cycle reporting system should be built based on coal production – washing - power generation - resource utilization, and the market of allowance-based trade and projects-based trade should be explored and improved based on accounting for carbon credits and carbon emissions rights. Market mechanisms should further play a positive role in controlling GHG emissions.

5. Conclusions

In China, industrial parks' activities are the main factors affecting industrial development, GHG emissions and environmental pollution. However, carbon reduction indicators are not incorporated into the CE evaluation indicator system at the industrial park level, and most studies ignored the distinction between direct and indirect emissions within the CE framework. Thus research on the impact of the CE on the carbon emissions of industrial parks is insufficient.

This paper defined the CF boundary for typical coal-fuelled power industrial parks, developed and successfully implemented a life cycle model for accounting of the CF of such parks. Then, the positive and negative impacts of the CE on carbon emissions of coal-fuelled power parks from 2000 to 2016 were quantitatively analysed. The life cycle carbon emissions of coal-fuelled power parks increased from 2000 to 2014 (up to 3250 MtCO_2e) and then decreased, following the same trend for China's raw coal production and consumption. Power generation is the dominant contributor, with its proportion of emissions maintaining above 86%. The CE seems to increase the overall carbon emissions of coal-fuelled power parks. In China, it increased the life cycle CF to 89.4 gCO_2/kWh in 2016. However, accounting for energy substitution, CE was able to actually reduce carbon emissions. From 2000 to 2016, the carbon emissions reduction from methane and mining water utilization was approximately 250.4 $MtCO_2e$. Although there is still some uncertainty, we believe that our CF estimation is more accurate than that of the past studies. In addition, CE development and life cycle-based policy initiatives should be given more attention by the government and the industrial park management department.

Finally, the circular transformation of different types of industrial parks should be promoted in developing countries that are in the middle of industrialization. This is crucial to reduce carbon emissions and environmental pollution on a country-wide level. This study only selected coal-fuelled power industrial parks for empirical analysis. Future research should extend similar analysis to other kinds of industrial parks globally by using a similar systematic accounting method.

Acknowledgments

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Nomenclature

CE	Circular Economy
CF	Carbon Footprint
EIA	US Energy Information Administration
EPA	US Environmental Protection Agency
GAQS	General Administration of Quality Supervision, Inspection and Quarantine of China
GHG	Greenhouse Gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MEP	Ministry of Environmental Protection of China
NBS	National Bureau of Statistics
NDRC	National Development and Reform Commission of China
UN	United Nations

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.05.064.

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