Journal of Cleaner Production 244 (2020) 118712

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

An emissions accounting framework for industrial parks in China

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ARTICLE INFO

Article history:
Received 4 April 2019
Received in revised form
30 September 2019
Accepted 3 October 2019
Available online 4 October 2019

Handling Editor: Yutao Wang

Keywords:
CO_2 emissions
Industrial parks
Climate change
China

ABSTRACT

China has the largest number of industrial parks in the world. These parks are not only crucial for the country to accelerate industrialization but also to achieve its climate change targets. Constructing CO_2 emission inventories for industrial parks is the first step in analysing the park's emission patterns and designing low-carbon policies. However, most of the previous emission accounts for industrial parks adopted various scopes and methodologies, making them incomparable with each other. This study develops a self-consistent methodology and framework for China's industrial parks based on enterprise-level data. We consider both Scope 1 and 2 emissions and construct the inventories by 19 energy types and 39 industrial sectors, which are consistent with the existing national, provincial, and city-level emission inventories. Such sectoral-based emission inventories will be not only able to provide data support for the design of emission/energy control policies, but also help the central/local governments evaluate a park's emission reduction performance. Finally, an empirical study is applied to four industrial parks to verify the method. In addition, we review the eco-industrial park programmes in Japan and South Korea, as well as their emissions accounting framework. We find that most of the Japanese industrial parks provide Scope 1, 2 and 3 emissions, while for South Korea, parks mostly focus on Scope 1 emissions. The discussion of Japan and South Korea's eco-industrial parks have referential significance for the construction China's low-carbon parks.

1. Introduction

Industrial parks can be defined as a specific area (tract of land) and zoned specifically for the location of industrial facilities. Industrial parks can accelerate national economic growth and maximize the industries' comparative advantage (Schmitz, 1995). At the same time, the development of industrial parks have also generated significant negative environmental externalities (Word Bank, 2018). Scholars have discussed the low-carbon development of industrial parks since the early 2000s (Côté and Cohen-Rosenthal, 1998; Hashimoto et al., 2010; Lehtoranta et al., 2011).

China has the largest number of industrial parks in the world (over 2534 national and provincial industrial parks) (NDRC, 2018) and more than 60% of the country's industrial output is generated by industrial parks. Considering that industry is China's primary consumer of energy (60% of the country's total consumption) and energy-related CO_2 emissions (85%) source (Shan et al., 2018b), managing energy and CO_2 emissions in industrial parks is essential for achieving the country's climate change mitigation targets and realizing low-carbon transformation.

Constructing emission inventories is the first step to analyse the industrial parks' emission patterns and further identify their driving factors and constraints. Accurate emissions accounting of industrial parks has the benefit of helping industrial parks design specific climate strategies and also helping the government evaluate the parks' low-carbon achievements.

Many studies have discussed the accounting methods or framework at the national or regional level. For example, the Intergovernmental Panel on Climate Change (IPCC) recommends an emissions inventory framework for countries (IPCC, 2006). The National Development and Reform Commission (NDRC) has developed a series of guidelines for provincial greenhouse gas inventories in China (NDRC, 2011). Some additional studies even focused on a finer scale: the city level (Chen et al., 2019; Li and Chen, 2013; Li et al., 2013). Shan et al. (2018a), Shan et al. (2019) and Ramaswami et al. (2017) individually developed city-level

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https://doi.org/10.1016/j.jclepro.2019.118712

emissions accounting frameworks. WRI et al. (2014) and ICLEI (2009) provided bottom-up methods for the compilation of city emission inventories (Yang et al., 2016).

Compared with the national or regional level, estimating the CO_2 emissions for industrial parks is more challenging, mainly due to the lack of consistent accounting methods and data source. The industrial parks, most of which have specific characteristics of industrial clustering, need their accounting methods to be detailed at the corporate/industrial sector level. The emissions accounting methods designed for administrative units (country/province/city) are not appropriate for park-level emissions accounting. Enterprise-specified activity data and emissions factors are needed to construct emission inventories for the industrial parks, i.e. using a bottom-up approach.

Therefore, few studies have attempted to calculate the CO_2 emissions for industrial parks, or propose low-carbon strategies for them (Wei and Liao, 2014; Xiong and Liu, 2013). For example, Gibbs and Deutz (2005) suggested developing eco-industrial parks in the USA in 2005; Roberts (2004) used an eco-industrial park in Australia as a case study to discuss its sustainable industrial development; and Tudor et al. (2007) reviewed the literature on drivers and limitations of eco-industrial park development. As for studies of China's parks, Geng et al. (2009) designed a new standard to evaluate national eco-industrial parks. The indicators included both carbon emissions and air pollutants. Carbon emissions is a key indicator for eco-industrial parks' construction, Lv et al. (2015) developed a method to calculate the CO_2 emissions of China's industrial parks, which was based on the IPCC and NDRC guidelines and included both Scope 1 direct emissions from fossil fuel combustion and indirect emissions from imported electricity/heat consumption. Liu et al. (2013) calculated only the Scope 1 energy-related emissions from several sectors of Suzhou industrial park, such as industrial production, transportation, and construction. Zhang et al. (2013) calculated the greenhouse gas emissions from different sectors, including energy consumption, waste deposition, and cement production, and used the industrial park located in Shandong Province as a case study. Liu et al. (2014) estimated the Scope 1 and 2 greenhouse gas emissions from the Beijing Economic Technological Development Area. This method included seven greenhouse gases: CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3. The first six are listed in the Kyoto Protocol, while NF_3 is largely emitted in electronics manufacturing. Yu et al. (2015) evaluated the emissions from the Xinfa Group. Several scenarios were discussed for emission reduction policies. Furthermore, some other studies calculated the Scope 3 emissions (from the perspective of consumption) or evaluated the environmental performances of industrial parks in China. For example, Chen and Yang (2017) compared current methods used for three scopes of emissions accounting at the industrial park level. Dong, H.J. et al. (2013) applied the hybrid life cycle analysis (LCA) model to calculate the consumption-based carbon emissions (carbon footprint) of the Shenyang Economic and Technological Development Zone.

After comparing these previous studies, this study finds that these previous methods contain large uncertainties regarding data measurement, data collection, and calculation methodologies. These uncertainties lead to inconsistent results. Most of the previous emissions accounting methods were designed for one or two specific industrial parks, and as a consequence the methods cannot be used universally. Different studies have different accounting scopes and subsequently produce the emission inventories for different sectors/energy types, making the emissions of different parks inconsistent and incomparable with each other (Li and Wang, 2014; Xie et al., 2010). Additionally, the reliability and appropriateness of previous methods remain unknown. To achieve a comparative analysis of CO_2 emissions across industrial parks and a multi-resolution emissions assessment in China, we should develop a robust, transparent, and standard carbon emissions accounting framework for industrial parks.

This paper addresses the gap by proposing a universal emissions accounting framework for industrial parks in China. The framework that has been developed is based on our previous studies on national/provincial/city-level CO_2 emissions accounting (Shan et al., 2016a, 2017, 2018b). The park-level inventories constructed by this new accounting framework will have the same accounting scope, method and format as China's national and regional inventories, making them self-consistent and comparable with each other. The park inventories include CO_2 emissions from both fossil fuel combustion (i.e. Scope 1 direct emissions) and purchased or imported heat and electricity consumption (i.e. Scope 2 indirect emissions). 19 energy types (17 fossil fuels plus heat and electricity) and 39 industrial sectors are covered in the emission inventory. In particular, when calculating the Scope 2 indirect emissions from heat and electricity consumption, we use the park-specific emissions factors to achieve an accurate account of the emissions.

We consider the most comprehensive and complex situations of the industrial parks. The framework can be applied to various types of industrial parks with different economic and energy structures. Following the framework, industrial parks in China can develop CO_2 emission inventories that are consistent with each other, as well as with inventories of other resolutions in terms of scope, format, and method.

The following sections are designed as follows: Section 2 introduces the development of low-carbon industrial parks in China, Japan, and South Korea. Section 3 develops an emissions accounting framework for China's industrial parks. Section 4 tests and verifies the accounting framework by conducting an empirical study on four industrial parks in China. The selection of the case parks is based on geographic and data diversity from the National Low-Carbon Industrial Park Pilot Programme (LCIPPP). Section 5 presents the conclusions.

2. Low-carbon development of industrial parks

While facilitating economic growth, industrial parks also bring severe resource and environmental challenges. Recent years have shown that a number of countries are seeking possible low-carbon development pathways for industrial parks. For example, China initiated the National Low-Carbon Industrial Park Pilot Programme (LCIPPP), and South Korea and Japan have also launched several programs to develop their own eco-industrial parks, which have led to significant achievements.

2.1. Low-carbon industrial parks in China

Industrial parks have made significant contributions to China's economic growth, yet have also caused serious environmental issues, such as greenhouse gas/air pollutant emissions and water pollution (Dong, L. et al., 2013; Wang et al., 2013). The direct and indirect energy-related greenhouse gas emissions of 213 Chinese national-level industrial parks were 1042 and 181 million tonnes CO_2 equivalent in 2015, respectively. These amounts account for 11% of the national greenhouse gas emissions for the year (Guo et al., 2018). Thus, industrial parks could be possible targets for the Chinese government to reduce its emissions and tackle climate change.

Considering the importance of the role industrial parks can play in addressing climate change, the Chinese government has already run a series of low-carbon programmes at the industrial park level to accelerate their low carbon transformation and their technologies innovation, especially for resource-based industries. For example, in 2013, the Ministry of Industry and Information Technology (MIIT) and NDRC jointly launched the National Low-Carbon Industrial Park Pilot Programme (LCIPPP). All pilot industrial parks were required to provide detailed emissions accounting and set emission reduction goals. The program has achieved remarkable progress and effectively raises the public consciousness of environmental protection. From 2014 to 2016, 51 industrial parks successively joined the LCIPPP (shown in Fig. 1) (Yu et al., 2018). The red triangles on the map illustrate the industrial park locations. The pilot industrial parks vary not only in location but also in many other aspects, including ‘pillar’ industrials, output, population, energy consumption and carbon emission. During the pilot period, most of the pilot parks maintained rapid economic growth, while significantly reducing energy consumption and carbon emissions. For example, the Yi Xing Industrial Park for Environmental Science & Technology and Jin Qiao Economic and Technological Development Zone decreased their emission intensities (calculated as per GDP emissions) by 8.01% and 8.06% during 2012–2016 (Yu et al., 2018).

2.2. Eco-industrial parks in Japan and South Korea

Similar to China, industrial parks also play a key role in South Korea and Japan, with most of their industrial upgrades being achieved by industrial parks. Both Japan and South Korea have promoted eco-industrial parks since the 1990s, and they have already delivered significant achievements. Their experiences can enlighten China’s low-carbon industrial parks development.

In 2013, South Korea developed 1033 industrial parks, including 41 state-level industrial parks, 528 general-purpose industrial parks, 11 municipal-level high-tech development zones, and 453 agricultural parks (Park et al., 2016). As for Japan, the eco-town project is one key programme that establishes innovative recycling activities in cities with voluntary initiatives by companies and financial support from the national government. The project aims to achieve a zero-emissions society through the promotion of advanced resource recycling and waste treatment technologies, as well as the development of environmental industry and a series of environmentally friendly cities. From 1997 to 2006, 26 local governments were sponsored for comprehensive recycling planning and waste treatment (Berkel et al., 2009; Sun et al., 2017). The eco-town project achieved significant greenhouse gas emissions reductions and natural resource conservation effects.

Japanese industrial parks have established relatively mature carbon accounting systems. For example, the eco-town project accounts for carbon emissions of different scopes in Japan, and the scopes of regional carbon emissions are the same as that shown in Table 1. In the Kawasaki eco-town, which was among the first four local government areas designated as eco-towns in 1997, the carbon emissions accounting scopes include Scope 1, 2 and 3. The total carbon emissions (Scope 1, 2 and 3) of the Kawasaki eco-town are 26,595 thousand tonnes of CO_2 equivalent, which include Scope 1 emissions of 26,006, Scope 2 emissions −6,630, and Scope 3 emissions of 7219 (Dong et al., 2014). The Scope 1 emissions include 21,656 thousand tonnes CO_2 equivalent from direct energy consumption, 4405 thousand tonnes from industrial processes, and 5.15 thousand tonnes from waste treatment. The “iron and steel manufacturing” sector is the dominant emitter of Scope 1 emissions, followed by the power sector. The Scope 2 emissions of Kawasaki eco-town in 2009 were −6630 thousand tonnes CO_2 equivalent because 79% of the power generated in the eco-town was sold to industries or residential areas outside the town. The

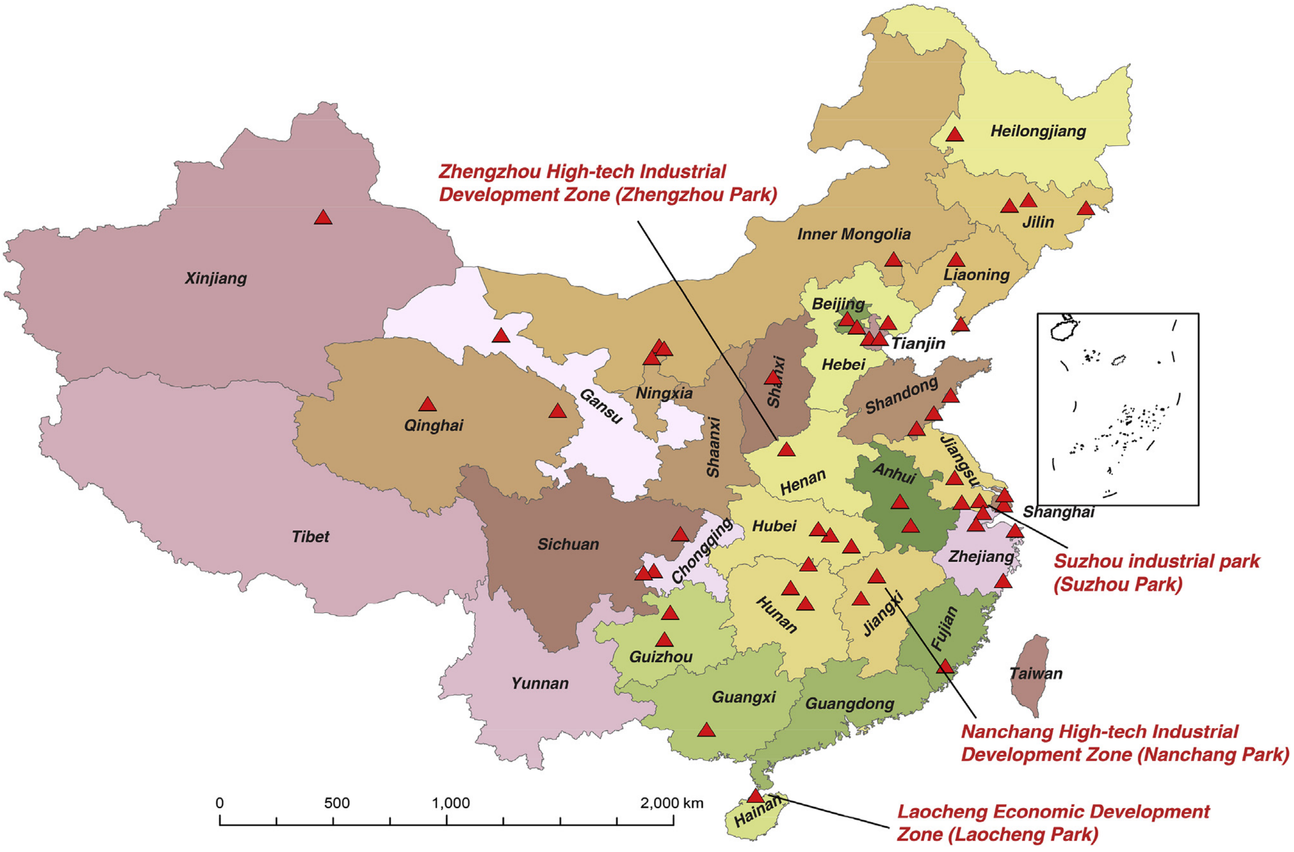

Fig. 1. Low carbon pilot industrial parks in China. The four industrial parks marked with names are selected as case studies in the following analysis.

Table 1
Scopes of regional emissions accounting (Kennedy et al., 2010).

Term	Spatial boundaries	Components
Scope 1	In-boundary emissions	Fossil fuel combustion, Industrial process and product use, Waste/landfill disposition emissions, Agriculture, forestry, and other land use emissions
Scope 2	In-boundary heat/electricity use	Out-of-boundary heat/electricity emissions at power plants
Scope 3	Out-of-boundary energy consumption	Aviation and marine fuel combustion, Imported products and services

Scope 3 emissions of Kawasaki eco-town were 7219 thousand tonnes CO_2 equivalent and included material consumption carbon emissions and depreciation carbon emissions, with values of 6491 and 728 thousand tonnes, respectively. Their data was sourced from questionnaire surveys and statistical departments for the cities and prefectures in which the parks are located (Ohnishi et al., 2012).

Currently, there are no CO_2 emission inventories for all industrial parks in South Korea, though some existing research has focused on the energy-saving and emission reduction effects of industrial symbiosis (Kim, H.-W. et al., 2018; Kim, H.W. et al., 2018s). Regarding CO_2 emission accounting, most of the studies provide Scope 1 only; if the accounting scope was extended to Scope 2 and 3, the results would be much different. For example, Ulsan city, a typical industrial city in South Korea, has developed the Onsan and Ulsan Mipo national industrial parks since 2005 via the national eco-industrial park (EIP) initiative. The Ulsan eco-industrial park focuses on energy symbiosis network construction, and 14 energy symbiosis networks of the high-grade heat were gradually established from 2004 to 2015. With the high- and low-grade waste heat exchange and utilization, the CO_2 emission reduction effect of 14 energy symbiosis networks was 487 thousand tonnes CO_2 in 2014.

Different low carbon polices and technical approaches have been applied to Japan and South Korea's parks. Eco-towns in Japan emphasize resource recycling and direct energy consumption, with eco-town projects focussing on the construction of sustainable waste management systems, that aim to combine municipal solid waste treatment systems with industrial systems, and promote the development of vein industry, material circulation and treatment. From the life cycle perspective, the eco-town project has shown great energy savings and emission reduction potential. The Korean EIP places more emphasis on energy symbiosis network construction. Under the complete market economy, the short investment payback period and considerable environmental benefits have encouraged enterprises to actively participate in industrial symbiosis networks. Their business model is successful, though from the perspective of emission reductions, there is still room for improvement, e.g. promoting raw material conservation and by-product exchanges.

3. Methodology

3.1. Accounting scope

Multiple industrial parks formulate and implement climate actions using different emissions accounting scopes. There are no uniform emissions scopes defined for industrial parks. Drawing on the scopes used for national and regional emissions accounting (WRI and WBCSD, 2014), this study identifies three scopes for industrial park emissions accounting, as shown in Table 1.

From Table 1, we can see that Scope 1 (also called IPCC administrative territorial emissions) are in-boundary emissions induced by fossil fuel combustion, industrial production, waste/disposition, agriculture and other sources. Scope 2 emissions refer to the emissions induced by in-boundary purchased heat/electricity consumption, i.e. electricity-related/heat-related emissions, respectively. The Scope 3 emissions (also called consumption-based emissions) are induced by out-of-boundary energy consumption, such as aviation and marine fuel combustion and energy consumed for imported products and services. The Scope 3 emissions reflect the emissions induced by the production of goods outside the regional boundary that are imported and consumed within the boundary via the trade chain.

Compared with Scope 3 emissions, both Scope 1 and 2 CO_2 emissions are calculated from the perspective of production. They describe the actual CO_2 emitted within the administrative boundary of an industrial parks, which can provide detailed policy implications for reducing emissions. Although Scope 3 emissions provide a further understanding of the emission landscape from the perspective of consumption, information on Scope 3 emissions does not have strong policy significance for reducing the emissions of one specific industrial park. When we explore the carbon emission reduction policies, or low-carbon development pathways for a specific industrial park, we focus on production-based emissions, which are emissions actually emitted within the park. To some extent, the Scope 3 emissions are more closely related to the interaction between industrial parks. Moreover, the Scope 3 emissions have very high data requirements (such as inter-park trade data) and accounting methods (such as economic models or life-cycle assessments).

In this way, our accounting framework involves both Scope 1 and 2 emissions. We consider the direct emissions from 17 fossil fuels' combustion for the Scope 1 emissions, including both final energy consumption and energy inputs for electricity/heat generation. As for the Scope 2 indirect emissions, we consider both the electricity/heat production (negative emissions) and consumption (positive emissions), in order to avoid double accounting with the Scope 1 emissions. In this way, overall 19 types of energy are included in our emission inventory (shown in Table 2).

The emission inventories are constructed by 39 industrial sectors (shown in Appendix Table1), which are defined according to the National Standard GB/T 4754—2011 (National Administration for Quality Supervision and Inspection and Quarantine of China, 2011), and the sectors are consistent with the System of National Accounts. We clustered the 39 sectors into four categories, i.e. energy production, heavy manufacturing, light manufacturing, and high-tech industries, for sectoral analysis (Shan et al., 2018a).

We collected the activity data (energy consumption) and calculated the emissions from individual enterprises in the industrial park. Each enterprise was allocated to one industrial sector to construct the emissions inventory of the industrial park.

3.2. Calculation methods

3.2.1. Scope 1 emissions from fossil fuel combustion

According to the IPCC (IPCC, 2006), the Scope 1 fossil fuel-

Table 2
Energy types and their emissions factors.

No.	Energy types in this study	NCV_i	CC_i	O_i
1	Raw coal	0.21	26.32	92%
2	Cleaned coal	0.26	26.32	92%
3	Other washed coal	0.15	26.32	92%
4	Briquette	0.18	26.32	92%
5	Coke	0.28	31.38	92%
6	Coke oven gas	1.61	21.49	92%
7	Other gas	0.83	21.49	92%
8	Other coking products	0.28	27.45	92%
9	Crude oil	0.43	20.08	98%
10	Gasoline	0.44	18.90	98%
11	Kerosene	0.43	19.60	98%
12	Diesel	0.43	20.20	98%
13	Fuel oil	0.43	21.10	98%
14	Other petroleum products	0.51	17.20	98%
15	Liquefied petroleum gas (LPG)	0.47	20.00	98%
16	Refinery gas	0.43	20.20	98%
17	Natural gas	3.89	15.32	99%
18	Electricity	Specified in each park		
19	Heat	Specified in each park		

Unit: NCV_i, $pJ/10^4 tonnes$ or $10^8\ m^3$; CC_i, $tonnes\ C/tJ$.

related CO_2 emissions can be calculated based on the mass balance theory shown in Equation (1).

$$CE_{ij} = AD_{ij} \times NCV_i \times CC_i \times O_i \tag{1}$$

In the equation, CE_{ij} refers to the CO_2 emissions induced by fossil fuel i's combustion in enterprise j, and AD_{ij} refers to the corresponding fossil fuel consumptions in enterprise j. The symbols NCV_i, CC_i, and O_i are the various emissions factors. NCV_i is the net caloric value of fossil fuel i, which refers to the value of heat released per unit of fuel i combustion. CC_i is the carbon content, which refers to the CO_2 emitted during per unit of heat released from fossil fuel i. O_i is the oxygenation efficiency, which refers to the fuel combustion ratio in boilers.

The CO_2 emissions induced by heat and electricity generation in the industrial park are calculated from the production side, i.e. calculated based on the fossil fuel combustion in power plants. The related emissions are accounted as Scope 1 fossil fuel-related emissions. Please note, that restricted by the data accessibility, enterprises do not provide detailed energy loss data during the generation of electric power and heat. We then assume all the energy inputs in power plants are combusted for electricity/heat generation when calculating the emissions.

Fuels input as raw material (such as raw coal inputs for plastic making and pharmaceutical uses) are removed from the corresponding enterprise's energy consumption. This part of energy consumption does not emit any CO_2 (Peters et al., 2006; Shan et al., 2016b).

3.2.2. Scope 2 emissions from imported/purchased electricity and heat

The Scope 2 CO_2 emissions induced by imported heat and electricity can be calculated using Equation (2) and Equation (3), respectively (IPCC, 2006).

$$CE_{heatj} = Heat_j \times EF_{heat} \tag{2}$$

$$CE_{elej} = Ele_j \times EF_{ele} \tag{3}$$

In Equation (2), CE_{heatj} refers to the Scope 2 heat-related CO_2 emissions from enterprise j, $Heat_j$ refers to the net imported (purchased) heat by enterprise j, and EF_{heat} is the emission factor for heat consumption, which refers to the CO_2 emissions embodied in the per unit heat generation. In Equation (3), CE_{elej} refers to the Scope 2 electricity-related CO_2 emissions from enterprise j, Ele_j refers to the net imported (purchased) electricity by enterprise j, and EF_{ele} is the emissions factor for heat consumption, which refers to the CO_2 emissions embodied in the per unit electricity generation.

It is worth noting that the net imported (purchased) electricity/heat values are calculated as the electricity/heat consumption value minus production. A negative result indicates that the enterprise produces more electricity/heat than it consumes, implying that the enterprise is an electricity/heat exporter. In contrast, if the net imported (purchased) electricity/heat is a positive value, the enterprise is an electricity/heat importer and has a positive Scope 2 emission value.

3.3. Emissions factors

3.3.1. Emissions factors for fossil fuels

Several research institutes have provided the emissions factors (NCV_i, CC_i, and O_i) for fossil fuels in China, including the IPCC (2006), NDRC (2011), Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al., 2017), and Emissions Database for Global Atmospheric Research (EDGAR) (Olivier et al., 2016). However, according to Liu et al. (2015)'s study on China's energy quality, the emissions factors provided by the IPCC are 40% higher than the actual condition in China. Therefore, this study adopts the most up-to-date emissions factors for fossil fuels, i.e. see Table 2 (Shan et al., 2018b). The O_i values are defined as 92%, 98%, and 99% for coal-, oil-, and gas-related fuels, respectively.

3.3.2. Emissions factors for heat/electricity

The NDRC provides the electricity emission factors for China's regional power grids (NDRC, 2013; Shan et al., 2016b). However, considering the different technique levels/cleaner energy mixes used in different industrial parks, the electricity emissions factors of different industrial parks may be different. In this study, we calculated the specific electricity emissions factors for industrial parks using Equation (4). The equation is derived with an inverse logic of the IPCC emission estimation equation (Equation (3)) (IPCC, 2006).

$$EF_{ele} = CE_{ele}/Prod_{ele} \tag{4}$$

In the equation, CE_{ele} refers to the total CO_2 emissions induced by the fossil fuel inputs for electricity generation in the energy enterprises, and $Prod_{ele}$ refers to the overall generation of electricity by all of the energy enterprises in the industrial park. Similarly, the emission factors for heat can be calculated using Equation (5).

$$EF_{heat} = CE_{heat}/Prod_{heat} \tag{5}$$

When one industrial park does not have any power plants, both Equation (4) and Equation (5) are ineffective. We then suggest using the NDRC default emissions factors, which represent the regional average technical level, to calculate the electricity/heat-related CO_2 emissions for the industrial park.

4. Empirical study of four industrial parks

4.1. Case parks

To verify the emissions accounting framework, we applied the method to four industrial parks: Suzhou industrial park (Suzhou Park), Nanchang High-tech Industrial Development Zone (Nanchang Park), Laocheng Economic Development Zone (Laocheng

Park), and Zhengzhou High-tech Industrial Development Zone (Zhengzhou Park). The four parks were selected based on geographic and data diversity.

Suzhou Park is located in Jiangsu Province, and there are more than 2000 enterprises in the park. Representing a typical large-scale mixed industrial park, most of its enterprises are considered high-tech industries, such as new materials, nanotechnology, electronics/information technology, and bioengineering/pharmaceutical. In addition, Suzhou Park comprises six energy-intensive enterprises, which accounted for approximately 15% of its gross industrial output in 2012. The park participated in the LCIPPP in 2013, and has witnessed a gradual annual decline in total carbon emissions while economic growth continued to increase during the pilot period of 2014–16. Its average economic growth from 2012 to 2016 was 7% and covered more than 10% of Suzhou's total economic outputs.

Moreover, Suzhou Park has made significant efforts to build its emissions accounting system, identifying 53 key units as work objects and subjects for greenhouse gas emissions reporting. Training was conducted on greenhouse gas emissions reporting for 12 key enterprises in the glass, electric power, chemical, ceramics, magnesium smelting, and steel industries and the park also entrusted third-party agencies to conduct on-site verification of the greenhouse gas emissions of enterprises and to identify the carbon footprints of products.

Nanchang Park, located in Jiangxi Province, has formed a low energy-intensive and high-quality green industrial structure based on aviation, optoelectronics, new materials, biomedicine, and new material development. The park had an average economic growth of 11% from 2012 to 2016. The total GDP of the park in 2015 was 31.6 billion Chinese yuan. The park has implemented a series of policies to control its energy consumption and carbon emissions and has seen its energy intensity and carbon emission intensity decreased by 31% and 23% in 2016 compared with the 2012 level, respectively.

Laocheng Park, located in Hainan Province, is one of the five strategical development zones in China. The park relies on the energy production, petrochemical, software and information technology, new material development, and food processing industries. Before 2013, there were 149 industrial enterprises in the park, and these contributed to 60% of the park's total GDP. In 2015, the park's total GDP was 38.3 billion Chinese yuan.

Zhengzhou Park, located in Henan Province, was established in 1993, and further developed to a national-level development zone in 2000. In 2015, the park's industrial GDP was 43 billion Chinese yuan. Additionally, 36% (or 36 billion Chinese yuan) of its industrial output was contributed by the high-tech industries.

4.2. Data collection

4.2.1. Activity data

This study collected the activity data (energy consumption of each enterprise) using field investigations. The total energy consumption, energy inputs/outputs, and non-energy use of each enterprise are needed for the emission inventory compilation. We consider only enterprises with an annual main business revenue of 20 million yuan or more (namely, enterprises above the designated scale) because they overwhelmingly contribute to the energy consumption and economic growth of the parks.

Among the four parks, Suzhou and Laocheng parks had all necessary data. Nanchang and Zhengzhou parks did not have any energy production enterprises; therefore, no energy input and output data could be collected for those two parks.

4.2.2. Emissions factors for electricity and heat

As introduced in Section 3.3.2, this study uses the emissions from energy production enterprises and their electricity/heat outputs to estimate the specific electricity/heat-emission factors for each industrial park. There are four energy enterprises with energy transformation producing activities locate in Suzhou Park and three in Laocheng Park. Fig. 2 shows the energy flow in the energy enterprises of Suzhou and Laocheng parks. The energy data are aggregated by the energy enterprises. We can see that Suzhou park produces electricity with natural gas while Laocheng park use raw coal to produce electricity, that brings Suzhou park a relatively lower emission factors of electricity generation. Laocheng park has more comprehensive energy transformation system that includes both electricity generation and petroleum refining.

Taking Suzhou park as an example, Table 3 shows the energy inputs and outputs of the four energy enterprises in Suzhou Park. The total raw coal used for electricity generation was 597.42 thousand tonnes, while the natural gas consumption was 710.88 thousand m^3. Therefore, the CE_{ele} value was equal to 2630.47 thousand tonnes. The total generated electricity of the four energy companies, $Prod_{ele}$, was 4693.01 mWh. Thus, this study calculated the electricity emission factor for Suzhou industrial park as 0.561 $ton\ CO_2/mWh$, which was 40% lower than the average grid level (0.93 $ton\ CO_2/mWh$, east grid). Similarly, the electricity emission factor for Laocheng Park was calculated as 0.776 $ton\ CO_2/mWh$.

For Nanchang and Zhengzhou parks, there were no power plants located in the parks. We used the grid average emissions factors instead, which was 0.801 $ton\ CO_2/mWh$ (centre grid) (NDRC, 2011).

The heat emission factor for Suzhou Park was calculated as 0.09 $ton\ CO_2/10^6KJ$ based on energy inputs and heat outputs of the four energy enterprises in Suzhou park. As for Zhengzhou park, there is no heart generation enterprise, we use the provincial average heat emission factor, which was 0.12 $ton\ CO_2/10^6KJ$. There is no heat consumption in Laocheng and Nanchang parks.

4.3. Results

4.3.1. Total emissions and emissions by energy types

Fig. 3 describes the emissions of the four industrial parks in 2015. The total emissions are compared in sub figure e) and the sub-emissions for each energy source are presented in sub-figures a) to d). We find that Suzhou park had significant high emissions of 5505 thousand tonnes compared with the other three parks. This is mainly due to the large scale of Suzhou Park. The total GDP of Suzhou Park in 2015 was 173.8 billion yuan, while that of Laocheng, Nanchang, and Zhengzhou Parks are 38.3, 31.6, and 43.0, respectively. We divide the parks' total emissions by their GDP and get the emission intensity of the parks: 0.317 (Suzhou Park), 0.334 (Laocheng Park), 0.337 (Nanchang Park), and 0.148 (Zhengzhou Park) tonnes per 10 thousand yuan. Suzhou, Laocheng, and Nanchang Parks had similar emission intensities while Zhengzhou had a lower intensity (more than 50% lower). This is mainly due to the clean energy structure used in Zhengzhou Park. As the sub figure d) shows, there is no raw coal used in Zhengzhou Park. Also, Zhengzhou Park had more high-tech industries (discussed in section 4.3.2), which consumed less energy and produced higher economic outputs.

By investigating the detailed emissions by energy types, we may describe the emission patterns of the parks in more detail. Taking Suzhou Park as an example (shown in Fig. 3-a), our results show that the total carbon emissions of the park was equal to 5504.7 thousand tonnes, in which Scope 1 emissions were valued at 4135, and Scope 2 emissions were valued at 1370. From the Scope 1 emissions, coal and natural gas were responsible for 96% of the industrial park's carbon emissions, indicating the primary energy use of the industrial park. Although raw coal and natural gas had

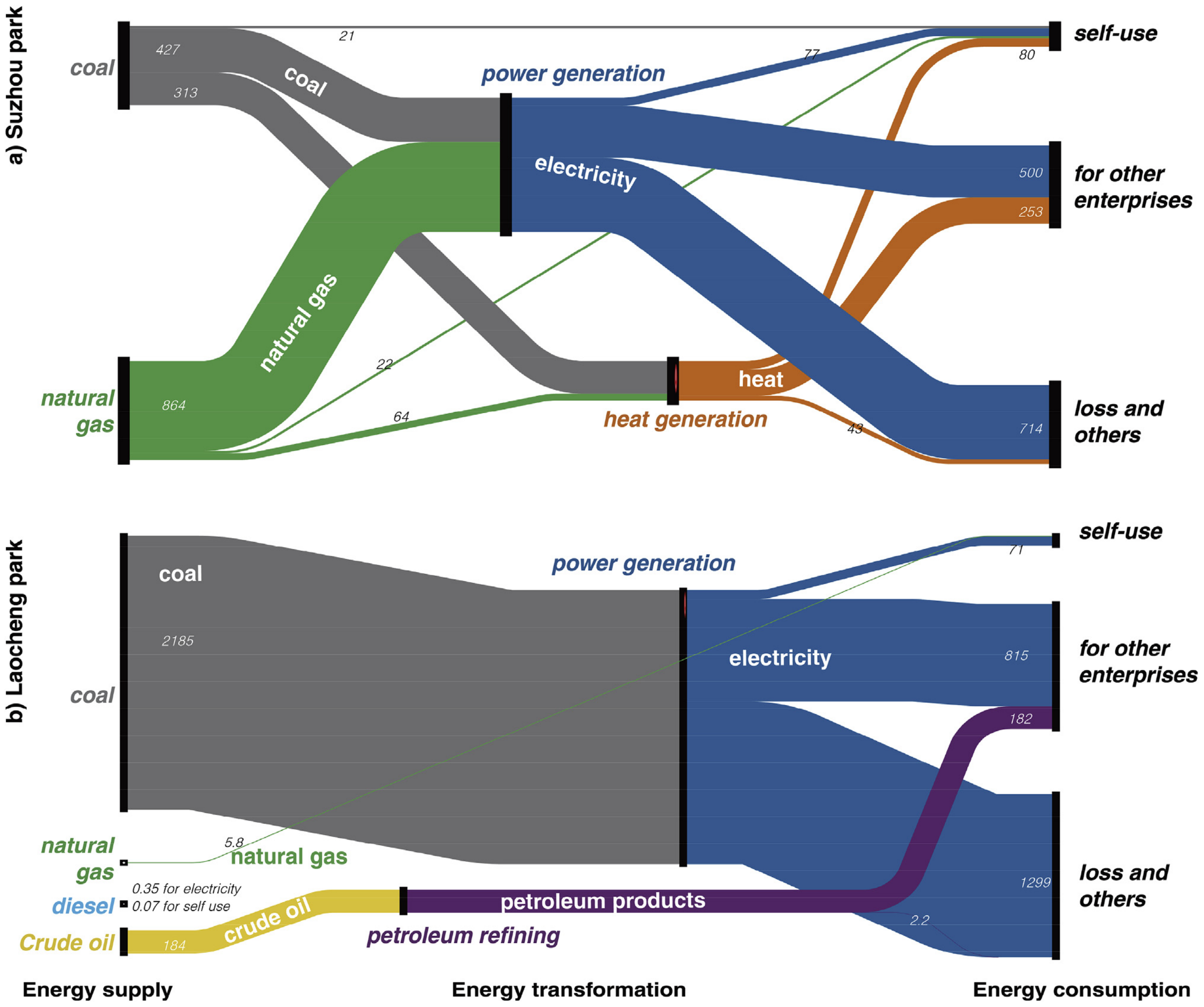

Fig. 2. Energy use in energy enterprises of Suzhou and Laocheng parksUnit
: tonnes of standard coal equivalent.

Table 3
Energy inputs and outputs of four energy enterprises in Suzhou park.

Energy enterprises		A	B	C	D	Total
Raw coal	Total consumption	0	721459	301782	40933	1064174
	Transformed inputs	0	692656	301782	40933	1035370
	Power inputs	0	416735	178051	2631	597417
	Heat inputs	0	275920	123731	38301	437953
Natural gas	Total consumption	34489	1786	0	41841	78116
	Transformed inputs	34489	0	0	41841	76331
	Power inputs	33599	0	0	37490	71088
	Heat inputs	891	0	0	4352	5242
Heat	Total consumption	0	2357573.45	0	0	2357573
	Transformed inputs	0	0	0	0	0
	Power inputs	0	0	0	0	0
	Heat inputs	0	0	0	0	0
	Total outputs	312054	4756805	2541660	2149942	9760461
Electricity	Total consumption	2589	49473	6211	4071.7	62345
	Transformed inputs	0	0	0	0	0
	Power inputs	0	0	0	0	0
	Heat inputs	0	0	0	0	0
	Total outputs	159697	88443	43433	177728	469301

Unit: raw coal, *tonnes*; natural gas, 10^4 m^3; heat, *million kJ*; electricity, 10^4 *kWh*.
Note: due to the data protection policy, we cannot disclose the names of the enterprises.

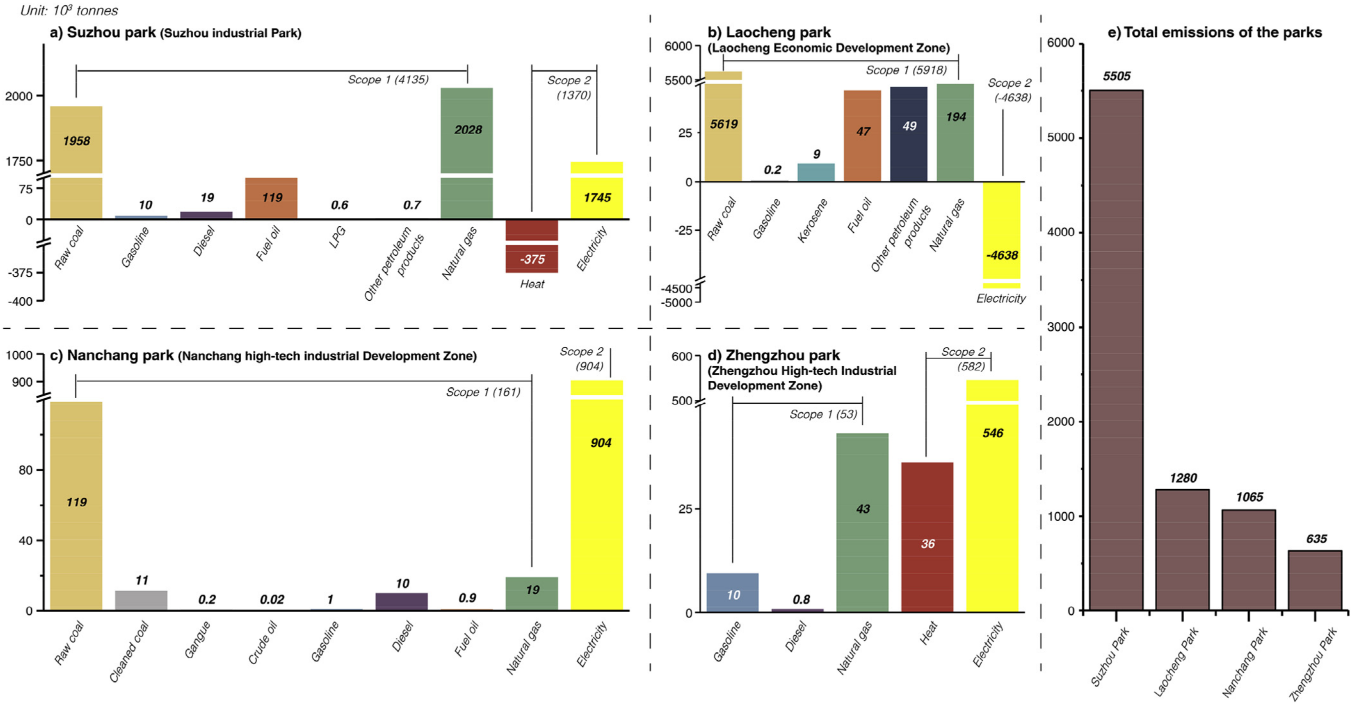

Fig. 3. CO_2 emissions of the four industrial parks in 2015.

approximately the same share of the Scope 1 carbon emissions (i.e. 47% vs. 49%), natural gas was more widely used, with 20% of enterprises consuming natural gas. In contrast, raw coal-related carbon emissions were induced by only four enterprises that were influenced by the electricity supply, textile, and paper-making industries. An overwhelming 99% of the total carbon emissions of raw coal combustion were from electricity production and supply enterprises. These two enterprises have been identified as significant components that must be considered if the low-carbon transition of industrial parks is to be achieved. Given that only 34% of the total enterprises in the park use raw coal and natural gas, this value indicates that the industrial park is relatively clean in comparison with the regional-level value, where natural gas accounted for only 5% of the total carbon emissions of Jiangsu Province in 2015 (Shan et al., 2018b). The electric power and steam supply represented the main consuming sector, and half of the carbon emissions from natural gas were supplied by this sector.

In addition to the emissions from primary energy, electricity is the major energy used in Suzhou Park, with 97% of enterprises consuming electricity. There are 3946 thousand tonnes of carbon emissions caused by electricity use in non-energy production enterprises; of these, 47% are from the manufacturing of electronics and telecommunications equipment and 10% are from the manufacturing of raw chemical materials and chemical products. The electricity plants produced only 2201 thousand tonnes of carbon emissions-equivalent electricity. That is, the electricity generated in the industrial park cannot meet the entire demand for electricity, which is evident by the 1745 thousand tonnes of carbon in the Scope 2 emissions value for the industrial park. In contrast, non-fossil heat produced in energy enterprises was a net export to areas outside the park, while enterprises in the park consumed heat that accounted for 319 thousand tonnes of carbon; moreover, 694 thousand tonnes of carbon emissions-equivalent heat was produced. Therefore, the net Scope 2 emissions in the industrial park were equal to 1370 thousand tonnes, contributing to approximately 25% of total Scope 1 + Scope 2 emissions; this result suggests Suzhou industrial park relies on energy purchased outside the park to meet its demands.

Laocheng Park emitted 5918 thousand tonnes of CO_2 in 2015, of which 95% was caused by raw coal. Natural gas contributed only 3% (or 194 thousand tonnes) to the total emissions. Most of the raw coal used in Laocheng Park is for electricity generation. There are two environmentally friendly power plants in the park, and these generated 7212 million kwh of electricity in 2015, with inputs of three million tonnes of raw coal and 239 tonnes of diesel. The emission factor of the two power plants is 0.776 $ton\ CO_2/mWh$, which is 15% lower than the Hainan grid's average emission factor (0.917 $ton\ CO_2/mWh$). Despite the large amount of electricity production in Laocheng Park, the park itself consumed only 1235 million kwh of electricity. Furthermore, 5977 million kwh of electricity was exported for usage outside the park. As a result, the Scope 2 emissions of Laocheng Park is −4638 tonnes.

Nanchang and Zhengzhou parks have a plain emission structure, as shown in Fig. 3-c and -d. There are no energy production enterprises in the parks, and electricity is the primary energy source that is used. The total emissions (Scope 1 and 2) of Nanchang and Zhengzhou parks are 1065 and 635 thousand tonnes of CO_2, respectively, of which electricity contributes 85% and 86%, respectively. Apart from electricity, raw coal is the second largest source of emissions in Nanchang Park (119 thousand tonnes, or 11%), and natural gas is the second largest source of emissions in Zhengzhou Park (39 thousand tonnes, or 6%).

4.3.2. Scope 1 and 2 emissions by sectors

To illustrate the detailed industrial structure of the emissions patterns of the four industrial parks, this study analysed the sectoral emissions of each park, and the results are shown in Fig. 4. The Scope 1 emissions are shown as the orange bars, while the green bars represent the Scope 2 emissions. There are only 32 kinds of sectors in the four parks, rather than a full category of 39 sectors (as shown in Appendix Table1). Some energy production or energy-intensive industries are not allowed in the parks. Therefore, Fig. 4

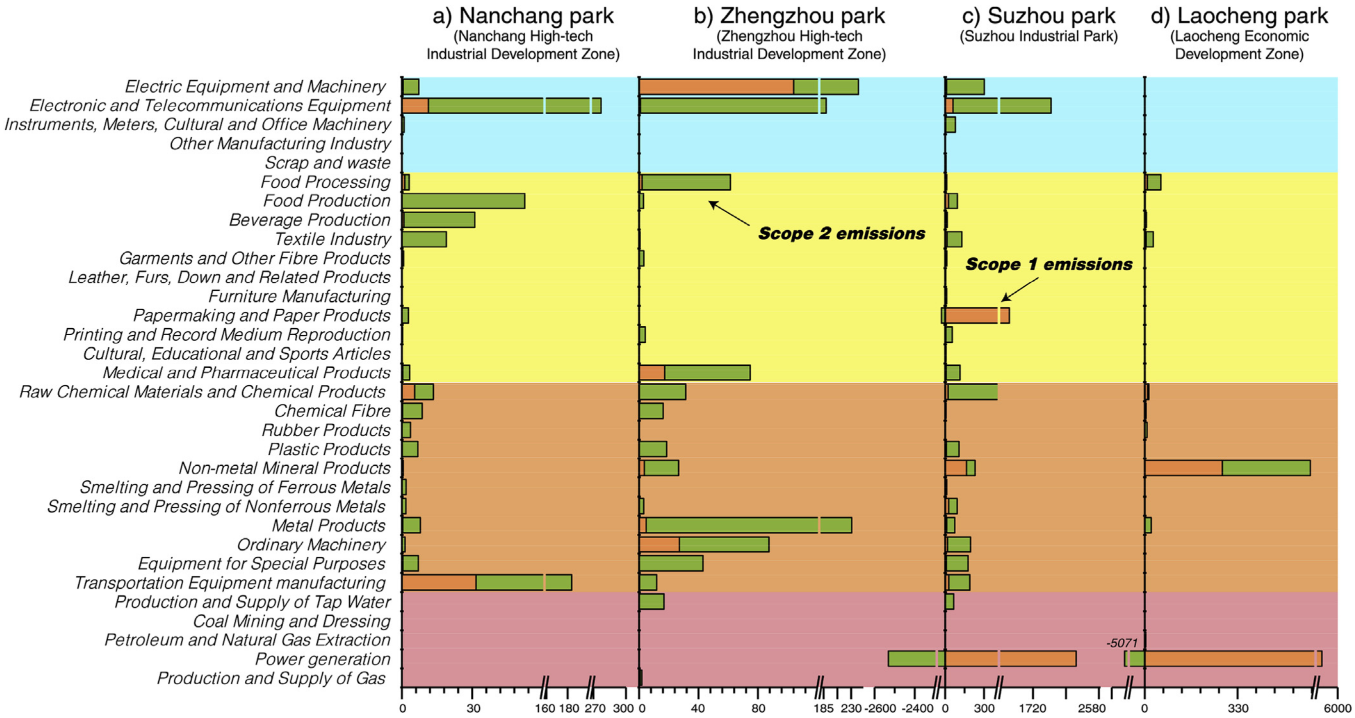

Fig. 4. Scope 1 and 2 emissions by sectors of the four industrial parks. The sectors with blue backgrounds belong to the high-tech industries, while the sectors in yellow/orange/red are part of the light manufacturing/heavy manufacturing/energy production industries, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

present only 32 sectors. We further classified the sectors into four clusters, including the high-tech industries (blue background), light manufacturing industries (yellow), heavy manufacturing industries (orange), and energy production industries (red) (Shan et al., 2018a).

Comparing the four parks, we found that Laocheng Park had the simplest industrial structure. Nanchang and Zhengzhou parks did not have any energy production enterprises; however, they gathered more high-tech and heavy manufacturing industries. Suzhou Park had the most comprehensive industrial structure among the four parks.

Using Suzhou Park as an example, we found that the power sector was the dominant emitter of Scope 1 emissions, contributing to 88% of the total CO_2 emissions. After offsetting the emissions embodied in purchased electricity and heat, the total Scope 1 + 2 emissions from the electric power and steam supply were equivalent to 752 thousand tonnes, which implied that the electricity and heat used by these energy enterprises embodied that total amount of emissions. In Suzhou Park, four sectors represented the main consumers of purchased energy, in which the electronic and telecommunications equipment represented the largest carbon emitter in terms of the Scope 1 + 2 emissions, values at 1955 thousand tonnes. The manufacturing of raw chemical material products, papermaking, and electricity equipment had much higher Scope 2 emissions than Scope 1 emissions. This result indicates that these sectors relied more on the electricity purchased from the electricity sector in the park or outside of the park, which demonstrates that emissions embodied in the energy supply chain could be more important than the mitigation policy focussing on primary energy for the non-energy sectors. Given the role of the electricity power and steam supply in the energy supply chain of the industrial park, a reduction in their Scope 1 emissions could help with the low-carbon transition at the industrial park scale. Despite natural gas being widely used in the electricity sector, half of the Scope 1 emissions were still from the raw-coal combustion found in electricity and heat production. Thus, switching the primary energy used by these enterprises should be a priority in implementing mitigation techniques.

4.4. Low-carbon strategies for the parks

The detailed analysis of the carbon emissions patterns identified the key sources of emissions in each park and shed light on potential emission reduction policies. We suggest that the policies should be designed to consider both Scope 1 and Scope 2 emissions. For the policies related to Scope 1 emission reductions, we suggest optimizing the parks' energy mixes and improving the production efficiency of various enterprises. Using Suzhou park as an example, despite the fact that coal-related fuels account for 47% of the park's emissions, which is much lower than the national average level of 82% (Shan et al., 2018b), there is still the potential for reductions if the park replaces raw coal with cleaner energy (such as natural gas) or renewable energy (such as solar power or wind power). We also propose that advanced techniques can be used to improve production efficiency, which could reduce emission intensity, i.e. producing more economic outputs with less energy inputs. Suzhou Park has already built a mature industrial structure that is dominated by high-tech enterprises; there may not be much room for carbon emissions reductions via structure optimization, but Laocheng Park could achieve more emissions reductions if it optimized its industrial structure towards a cleaner and more high-tech approach.

From the perspective of Scope 2 indirect emissions, we found that Suzhou and Laocheng parks had more efficient and cleaner electricity generation lines in terms of their power plants. Their emission factors of electricity production were 31% and 15% lower than the national grid's average level, respectively. Therefore, we encourage these parks to produce more electricity to meet their own demand and to also support their surrounding areas if possible. When necessary, the park should choose clean electricity when purchasing external electricity. Considering the outsourcing effects of emissions, energy supply chains outside the industrial park should be scrutinised as well.

5. Conclusion

With an increasing number of industrial enterprises gathering geographically and forming industrial parks in China, more specific low-carbon strategies should be designed at the park level in order to achieve the country's emission reduction goals and fulfil local climate mitigation and adaptation. Understanding the industrial-park level emissions characteristics is the very first and foundational step of any further climate change actions.

This study develops a self-consistent methodology and framework for park-level emission inventory construction in China. The emission inventories include both Scope 1 emissions from fossil fuel combustion and Scope 2 emissions induced by imported electricity and heat. We use the park-specific emission factors of imported electricity/heat to achieve an accurate account of the park's emissions. The inventories are constructed as 19 energy types and 39 industrial sectors, as this approach is consistent and comparable with the System of National Accounts and national/regional emission inventories. Despite the fact that different industrial parks may have different industrial structures and energy mixes, this integrated emissions inventory construction framework adapts to all types of industrial parks. By adopting the construction framework, different industrial parks can achieve comparable emission inventories comprising the same scopes and formats. In addition, this park-level emissions accounting method is consistent with our national and regional emission inventories in China, making the emissions comparable from a multi-scale perspective.

To test and verify the method, we chose Suzhou, Laocheng, Nanchang, and Zhengzhou parks as empirical studies and compiled the 2015 emission inventories for the parks. Possible low-carbon strategies are discussed for the parks combing our accounting results. We propose the policies should be designed to consider both Scope 1 and Scope 2 emissions. From the view of Scope 1 emissions, parks can optimize their energy structure and apply advanced techniques to improve production efficiency. There might not be that much potential for emissions reductions via industrial structure optimization, because parks usually have assigned development roadmaps, which is designed based on local government's need and comparative advantages. Also, some parks have already had the most advanced industrial structures. From the aspect of Scope 2 emissions, some parks have developed more efficient and clean electricity/heat production lines (such as Suzhou and Laocheng), in this case, we encourage these parks to produce more electricity/heat to meet their own demand and to also support their surrounding areas if possible.

It is noteworthy that there are still many gaps in mitigating emissions from industrial parks. Tailoring the mitigation pathways for thousands of industrial parks requires an immense effort in terms of the carbon inventory construction. We hope our study inspires and offer insights that are relevant to subsequent studies.

Declaration of competing interest

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

Acknowledgements

This study is supported by the British Academy and Chinese Academy of Social Sciences Newton Advanced Fellowships (AF150310); and additional funding came from the Chinese Academy of Social Sciences (2017YCXZD007); the Chinese National Funding of Social Sciences (16BJY046). The authors thank the Suzhou industrial park, Nanchang high-tech industrial development zone, Laocheng economic development zone, and Zhengzhou high-tech industrial development zone.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118712.

Appendix

Appendix Table 1
Industrial sectors

No.	Industrial sectors	Classifications
1	Coal Mining and Dressing	Energy production
2	Petroleum and Natural Gas Extraction	Energy production
3	Ferrous Metals Mining and Dressing	Energy production
4	Nonferrous Metals Mining and Dressing	Energy production
5	Non-metal Minerals Mining and Dressing	Energy production
6	Other Mineral Mining and Dressing	Energy production
7	Food Processing	Light manufacturing
8	Food Production	Light manufacturing
9	Beverage Production	Light manufacturing
10	Tobacco Processing	Light manufacturing
11	Textile Industry	Light manufacturing
12	Garments and Other Fibre Products	Light manufacturing
13	Leather, Furs, Down and Related Products	Light manufacturing
14	Timber Processing, Bamboo, Cane, Palm Fibre & Straw Products	Light manufacturing
15	Furniture Manufacturing	Light manufacturing
16	Papermaking and Paper Products	Light manufacturing
17	Printing and Record Medium Reproduction	Light manufacturing
18	Cultural, Educational and Sports Articles	Light manufacturing
19	Petroleum Processing and Coking	Energy production
20	Raw Chemical Materials and Chemical Products	Heavy manufacturing
21	Medical and Pharmaceutical Products	Light manufacturing
22	Chemical Fibre	Heavy manufacturing

Appendix Table 1 (*continued*)

No.	Industrial sectors	Classifications
23	Rubber Products	Heavy manufacturing
24	Plastic Products	Heavy manufacturing
25	Non-metal Mineral Products	Heavy manufacturing
26	Smelting and Pressing of Ferrous Metals	Heavy manufacturing
27	Smelting and Pressing of Nonferrous Metals	Heavy manufacturing
28	Metal Products	Heavy manufacturing
29	Ordinary Machinery	Heavy manufacturing
30	Equipment for Special Purposes	Heavy manufacturing
31	Transportation Equipment Manufacturing	Heavy manufacturing
32	Electric Equipment and Machinery	High-tech industry
33	Electronic and Telecommunications Equipment	High-tech industry
34	Instruments, Metres, Cultural and Office Machinery	High-tech industry
35	Other Manufacturing Industry	High-tech industry
36	Scrap and Waste	High-tech industry
37	Production and Supply of Electric Power, Steam and Hot Water	Energy production
38	Production and Supply of Gas	Energy production
39	Production and Supply of Tap Water	Heavy manufacturing

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