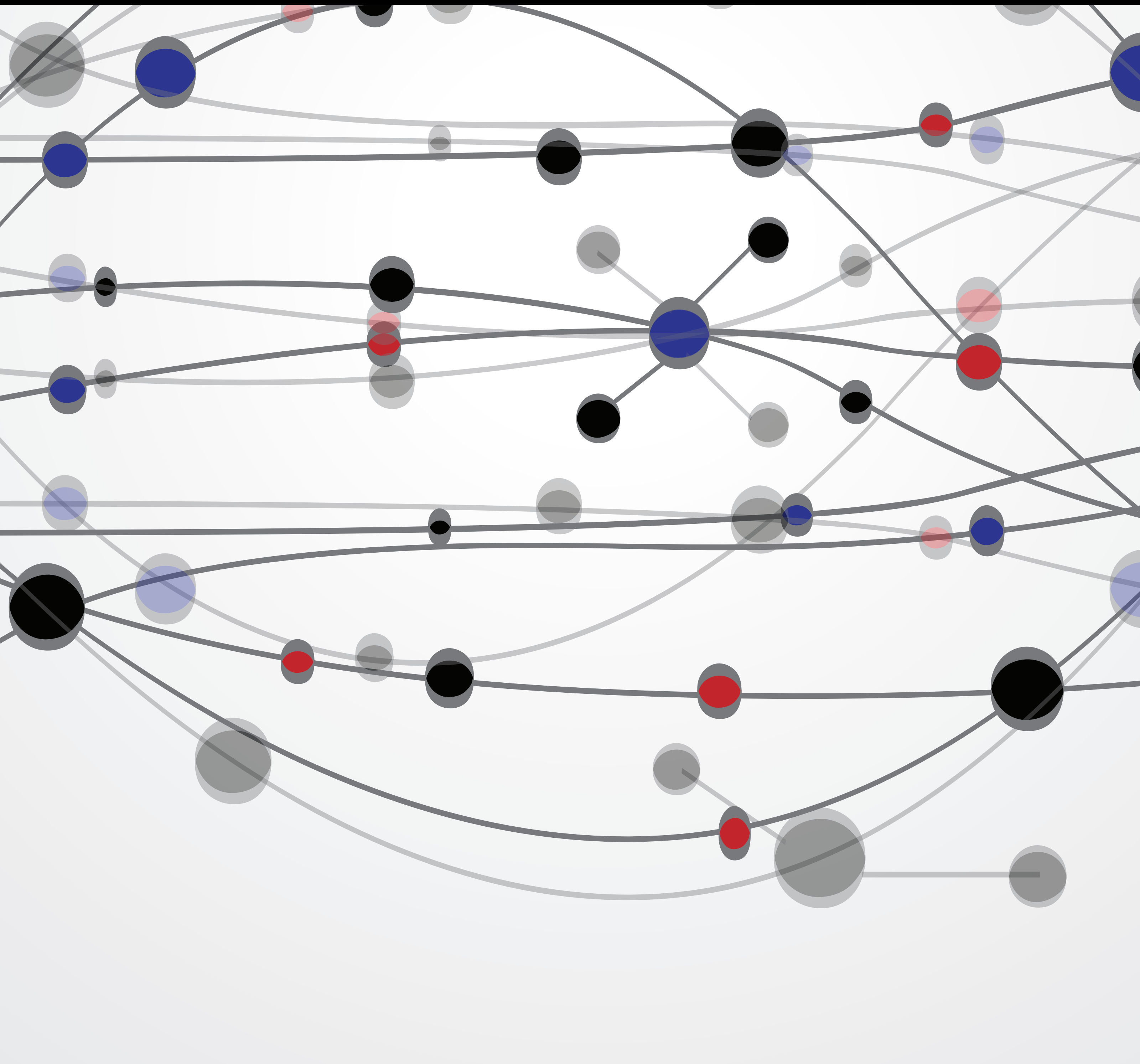
The Scientific World Journal

Energy Economics and Policy

Guest Editors: Zhan-Ming Chen, Bin Chen, and Han-Song Tang



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Contents

Hindawi Publishing Corporation
The Scientific World Journal
Volume 2013, Article ID 536517, 2 pages
http://dx.doi.org/10.1155/2013/536517

Editorial

Energy Economics and Policy

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Received 20 March 2013; Accepted 20 March 2013

There are emerging concerns worldwide on management of energy resources and its development, such as control of the environmental impact of energy use, regulation and expedition of the commercialization of renewable energy, and reevaluation of the safety issue of nuclear power. As a result, theoretical and empirical studies on energy economics and relevant policies are of emergent need to assess the performance of previous efforts as well as to guide future development. Especially, investigations on the characters of energy market and governments' roles in it are of significant implication for decision makers concerning different aspects of energy management.

20 papers selected from 36 submissions are published in this issue, which cover many important topics in the field of energy economics and policy. At the macroscale, P. Massot and Z.-M. Chen review the history of global uranium market and discuss the potential coexistence between the rising market of China and the rest of the world. X. H. Xia and Y. Hu use China's subprovince and prefecture level data to analyze the determinants of electricity consumption intensity. B. Zhang et al. provide an overview of resources use and environmental impact of the Chinese industry during 1997–2006 based on an exergetic assessment. The fossil fuels inputs in China during 2000–2010 are estimated by S. Wang et al. in a material flow analysis which takes hidden flows into account. Acknowledging the importance of infrastructure investment for the Chinese economy, the embodied energy use in China's infrastructure investment during 1992–2007 is evaluated by H. Liu et al. based on an energy input-output model. S. Lee et al. analyze the potential economic and environmental effects of carbon tax in Japan using a global macroeconometric model. In the study by F. Tao et al., the directional distance function and the Luenberger productivity index are applied to measure the industry efficiency and total factor productivity at the level of subindustry in China during 1999–2009. By employing an input-output model, S. Guo et al. construct an embodied greenhouse gases emissions inventory for Beijing. Fuel consumption and exhaust emissions, including nitrogen oxides and particulate matters, by China's auto industry are estimated and related mitigation policies are discussed by Wu et al. In P. Dai et al.'s paper, an integrate optimization model is proposed for mitigating carbon dioxide emissions from the power sector of China.

Other efforts are devoted to energy systems at smaller scales. In the light of the concept of low-carbon community, S. Song et al. propose a life-cycle-based accounting framework for carbon dioxide emissions and employ it to a case in Beijing. As an efficient mode to organize modern production, the industrial park attracts special attentions not only for its important role in economic development but also for its highly concentrated energy use. Four papers in this issue discuss different aspects of the industrial park: the sustainability performance of the industrial park is evaluated based on a life-cycle multicriteria framework by J. Yang et al.; the carbon metabolism of the industrial park is simulated in an ecological network analysis by Y. Lu et al.; the greenhouse gas inventory and ecological-economic benefits of the industrial park are discussed in two papers by B. Chen and his colleagues. Another two papers in this issue focus on renewable energy systems: Y. Wang et al. compare the ecological-economic value of two different biogas plants by an emergy method; Q. Yang et al. assess the nonrenewable energy cost and greenhouse gas emissions of a "pig-biogas-fish" agricultural system based on a life-cycle assessment. To analyze the incentive mechanism of power plant efficiency retrofit, D. Yuan et al. calculate the internal rate of return of an ordinary steam turbine coal-fueled power plant in China under different scenarios. The price elasticity of residential electricity demand is estimated by G. Shi et al. to fill the gap between data requirement for policy making and scientific research outcome. In a more technical research, Z. Wang et al. focus on light extraction efficiency improvement of light-emitting diodes.

In summary, economics analysis on energy systems and policies of their development is gaining more and more attention, and the papers presented in this special issue represent the current status of their research. Nevertheless, many problems remain unresolved, and more research is necessary. We look forward to new progress on the basis of and beyond the investigations reported in this issue.

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Hindawi Publishing Corporation
The Scientific World Journal
Volume 2013, Article ID 672060, 11 pages
http://dx.doi.org/10.1155/2013/672060

Review Article

China and the Global Uranium Market: Prospects for Peaceful Coexistence

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Received 7 November 2012; Accepted 14 February 2013

Academic Editors: T. Kojima, J. Niu, and D. M. F. Santos

China's recent reemergence has resulted in a significant increase in the global demand of commodities and is already having major impacts on the dynamics of global commodity markets. In the case of the global uranium market, we stand at the very beginning of a period of change. However, interesting trends are already emerging. Whereas China has had many policy reversals, and some difficulties in taking control of its procurement strategy in other commodity markets, it is seemingly more successful in managing its uranium procurement strategy. Why? The argument presented here is that a mixture of domestic and international level variables has allowed China more room for maneuver in fulfilling its uranium procurement strategy. On the domestic level, a centralized industry, and, on the international level, a geographically dispersed and uncoordinated market have allowed China to forge ahead with an ambitious civilian nuclear power plan and triple its total uranium imports, all within the span of a few years. Many challenges remain, not the least that of negative public opinion, which has surged since the Fukushima disaster in 2011. Nevertheless, should uranium demand continue to grow, this paper will consider the potential for continued peaceful coexistence among uranium market participants worldwide.

1. Introduction

China's fast development has resulted in a significant increase in the global demand of almost all commodities. This increased demand has already had major impacts on the dynamics of certain global commodity markets [1–6].

In the case of the global uranium market, we stand at the very beginning of a period of change. China's uranium demand has only started to increase significantly in the past 10 years. Moreover, if many analysts are arguing that Chinese demand for certain commodities may plateau or even fall in the near future, the situation is clearly different in the case of uranium. China has 16 operating nuclear reactors as of mid 2012, but it has 27 reactors under construction and plans to build at least another 50 in the coming years [7].

Another reason why China's interaction with the global uranium market is interesting is the room for manoeuver that China was able to carve for itself in this global market. Whereas China has had many policy reversals, and some difficulties in taking control of its procurement strategy in the global market of iron ore, for instance, it is having a better time managing its uranium procurement strategy. Why is China seemingly more successful in its entry on the global uranium market? Is this emerging trend likely to persist? Considering the fact that uranium demand is projected to go up substantially in the coming years, what is the potential for continued peaceful coexistence and cooperation among uranium market participants worldwide? This paper seeks to answer these questions in turn.

In sum, the argument is made that specific components of the structure of the international uranium market allow China more room for maneuver than in many other commodity markets and are influencing the way in which China chooses to engage with it. The global structure of the uranium market is relatively dispersed geographically but, more importantly, exhibits a lack of coordination among the existing market stakeholders; it has also suffered from underinvestment and lack of interest for decades leading to the early 2000s and thus was ripe for welcoming increased investment and involvement by an emerging actor such as China. On the domestic side of things, the importance given to China's civilian nuclear program by the government and the concentration of decision-making among few actors have allowed the country to manage existing challenges and effectively advance its overseas procurement strategy.

In terms of prospects for future peaceful coexistence, they can be realized if the recent international cooperation initiatives, which encourage transparency and collaboration, can create a virtuous circle. In an unexpected way, nuclear safety and security concerns, which lead to international cooperation mechanisms in the first place, beyond enhancing nuclear safety in China, could provide the impetus for more cooperation internationally. These international efforts have also showcased China as a country ready to rise to the occasion and be a responsible player, as a member of the International Atomic Energy Agency for instance.

After a short review of the history of the uranium market since its emergence, the consequences of the Fukushima nuclear accident and the global structure of the uranium market will be discussed. Thereafter, China's current growing resource needs as well as the domestic and international challenges it faces will be reviewed. This will be followed by an assessment of the current Chinese uranium procurement strategy. In conclusion, an analysis of China's participation in recent cooperation initiatives bilaterally and internationally will be made.

2. A Short History of the Uranium Market

First of all, "There are at least four markets in the front-end of the nuclear fuel cycle that must be reviewed to determine assurance of supply: (1) uranium mining and milling, (2) uranium conversion, (3) uranium enrichment, and (4) nuclear fuel fabrication." [8]. See also Conde and Kallis [9]. This paper will concentrate mainly on the first step, uranium mining.

2.1. Emergence—Atoms for Peace—Cartel Period. The uranium industry emerged in the late 1940s early 1950s, mainly for military purposes [10]. In 1953, the race for dominance in the area of civilian nuclear power was set in motion by the US Atoms for Peace program.

In the 1960s, the American Energy Agency banned the use of foreign uranium in its domestic reactors and aggressively cut prices of its own uranium exports. This was a period of oversupply in the rest of the world. The Canadian government decided to support its domestic uranium industry while stockpiling its inevitable surplus of uranium production.

It was then that Canada and other major uranium producers of the world (Australia, France, South Africa, and Rio Tinto Zinc Ltd.), in the absence of the US, sought to mitigate the impacts of the American policy and resorted to the covert manipulation of the world market [11].

In June 1972, the secret international uranium cartel was formally established (arrangements included price fixing, bid rigging, and market sharing). The cartel was referred to as the Société d'Études de Recherches d'Uranium (SERU).

Westinghouse filed an antitrust action against the cartel members, including a Canadian company, in 1976, and the cartel subsequently dismantled. We have not been able to find evidence that uranium producers have continued to coordinate their operations since then.

2.2. Oversupply and Fall in Prices. During the 1980s and 1990s, for a combination of reasons, including the end of the Cold War (and thus the increased availability of secondary sources of uranium), a lull in the construction of new nuclear power plants worldwide (because of the consequences of the Three Mile Island and Chernobyl disasters and a reduction in expected growth of electricity demand) resulted in a fall of the uranium spot price, and thus of mining production.

Indeed, from the early 1980s until 2001, uranium prices trended downward and remained between USD $7 and USD $10 a pound.

2.3. Price Bubble. Beginning in 2001, the price of uranium began to rebound from historic lows and continued to rise through 2007. The real bubble occurred during the year 2007, triggered by shrinking weapons stockpiles (and thus the decreased availability of secondary sources), a flood at the Cigar Lake Mine in Canada, expected undersupply due to a slew of reactors coming online, compounded by the relatively recent news of an extensive nuclear program expansion in China, as well as speculative pressures.

As the uranium price shot to historical heights of USD $136 a pound (see Figure 1), the extent of the twenty previous years of underinvestment in uranium production became all the more obvious.

2.4. Impact of Fukushima Crisis. The 9.0 magnitude earthquake in Japan was a uniquely severe natural disaster. So severe that the safety standards in place at the Fukushima power plant did not allow for such a magnitude. This was compounded by the impact of the tsunami.

The international consequences of the Fukushima disaster were substantial, first and foremost in Japan. As of August 2012, only 2 out of the 54 Japanese reactors are operating again [12]. The government's basic stance on dealing with the power shortage has so far been to beef up its efforts to reduce power consumption and increase thermal power generation. But the combination of a fall in energy output and increased disruptions of supply is likely to have a lasting negative impact on growth, as argue Weinstein and Schnell [13]. Indeed, as Japanese communities continue to oppose the reopening of nuclear reactors, the effect of the earthquake has translated in a sustained drop in industrial production. The Japanese Minister of Industry (Yukio Edano) was quoted as saying that it is "necessary to restart nuclear reactors to avoid power shortages, provided that it can be done safely and with the agreement of local residents" [14].

The civilian nuclear industry seems poised to draw the lessons from this event, but it can be expected that the improvement in nuclear safety measures as well as the implementation of more efficient emergency procedures should have an inflationary impact on overall costs, just as it was

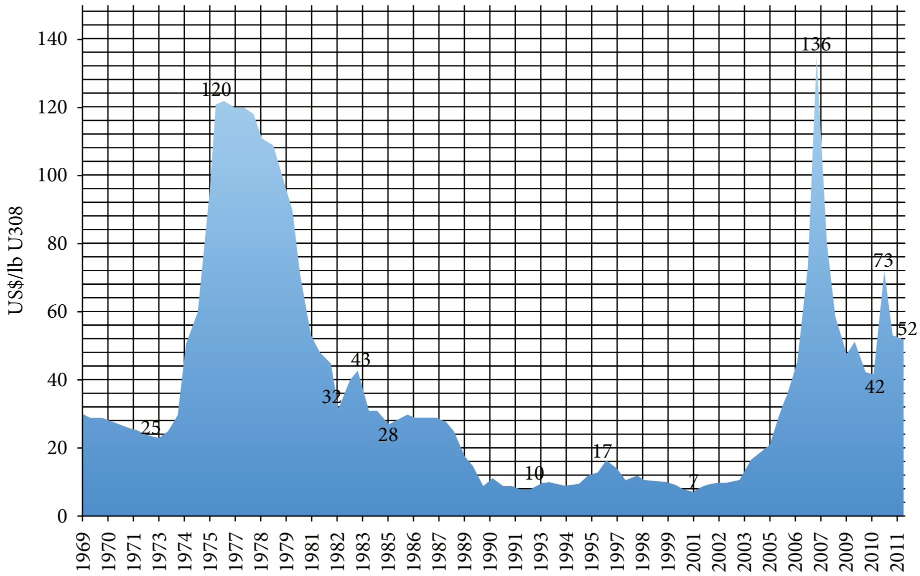

Figure 1: Uranium spot prices 1969–2012. Source: (1969–1989, NUEXCO Exchange Value, UX Consulting, constant 2007$; 1989–present, CAMECO, current$).

the case after previous major accidents [15]. Such expectations, as well as increased public opposition to nuclear power, resulted in a drop of uranium prices worldwide. Between February 2011 and August 2011, the spot indicator fell by around 30% from a high of USD $72.63 a pound to US $49.13 a pound.

In China, "five days after the earthquake and tsunami, the State Council suspended approval of new nuclear projects and started conducting comprehensive safety inspections of all nuclear projects—those in operation as well as those under construction. It also decided to halt four approved projects due to start construction in 2011" [16]. Chinese companies have responded to the changing global context by attempting to renegotiate outstanding bids and positions. In early May 2011, CGNPC withdrew its $1.24 billion bid to acquire a controlling interest in Kalahari Minerals PLC, which is developing a uranium mine in Namibia and then reopened the talks in the fall of 2011. A deal was finally struck again in February 2012 for close to $1 billion.

2.5. Current Prospects. In the end, however, many analysts argue that the impact of the Fukushima accident on uranium prices will be short-lived, since the projected drop in demand will most likely be more than compensated by growth in emerging countries. Indeed, it is expected that Asia will account for most of the growth in new nuclear reactors, of which 40 percent will come from China [17].

"Globally, (the CEO of CAMECO Tim) Gitzel said he expected uranium demand to grow about 3 percent a year in the "next few years." The "psychological" impact of the Fukushima nuclear accident in Japan will be in the "short-to-medium-term," he said [18].

Current analysts actually forecast a growing deficit in uranium supplies starting from now (shortfalls have been driven by either lower forecast prices compared to 2007, problems with existing operations or delays in new mine production). For instance, the Royal Bank of Canada Capital Markets argues that uranium price indicators are down from the 2007 bubble, but still up from the 2008 low, and foresees uranium demand growing by an average of 4% per year during the next 20 years. They project a price of $80 a pound for 2013 [19].

While the fact that Germany decided to phase out its civilian nuclear program by 2022 made the news following the Fukushima disaster, talks of a nuclear phase out of nuclear energy for commercial power generation purposes had been on the agenda in Germany since at least 2002. German uranium demand represents anywhere between 2300 [20] and 3800 tons annually [21], or less than 5% of global demand. All in all, the construction of reactors in China is expected to outweigh the decommissioning of plants in Germany, Japan, Belgium, Italy, and Switzerland.

Bullish price predictions are also supported by the fact that we are currently entering a key transition period for the uranium market. Current global uranium production meets around 75% of global demand, the rest being met by stockpiles (released from military sources), inventories of which are rapidly decreasing. Indeed, the US-Russian Highly Enriched Uranium (HEU) Purchase Agreement, which converts surplus HEU from Russian nuclear weapons into fuel for US commercial power reactors, is expiring in 2013 [19, 22].

This "Megatons to Megawatts Program is a unique, commercially financed government-industry partnership in which bomb-grade uranium from dismantled Russian nuclear warheads is being recycled into low enriched uranium (LEU) used to produce fuel for American nuclear power plants. USEC, as executive agent for the U.S. government, and Techsnabexport (TENEX), acting for the Russian government, implement[ed] this 20-year, $8 billion program. (...) In years past, up to 10 percent of the electricity produced in the United States has been generated by fuel fabricated using LEU from the Megatons to Megawatts program." [23].

The Director General of Rosatom says the contract will not be renewed in 2013. This will cause a gap of around 20,000 tons of uranium. Only around half of this gap will be filled through a new supply agreement that was signed between Russia's Techsnabexport (TENEX) and the United States Enrichment Corporation. Whereas the Megatons to Megawatts program was special in that it converted Russian nuclear weapon material, the new 2013–2022 supply agreement will provide the US with commercially enriched uranium from Russia [24]. Adding to the glut, many large uranium mines are currently close to depletion.

The uranium spot market reflected a persistent buyers' market over the 15-year period of 1980 to 1994, and again between 1998 and 2003 [25]. The situation is reversed to a significant degree now.

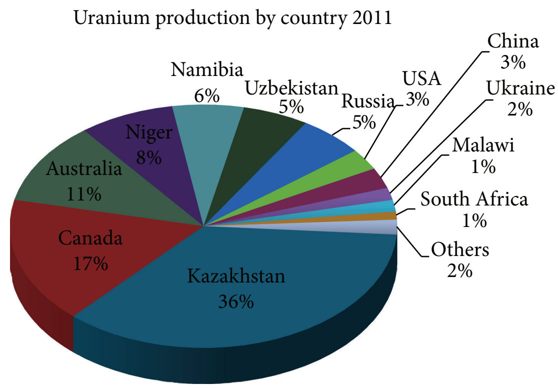

Figure 2: Uranium production by country in 2011. Source: Euratom Supply Agency, World Nuclear Association.

2.6. Uranium Spot Market. Due to its special history, uranium is not widely traded on an organized commodity exchange, such as the London Metal Exchange. Spot prices are responsible for no more than 15% of global trades. For instance, during 2008, about 48 million pounds of U_3O_8 changed hands in the spot auctions [26]. This is a relatively small quantity compared to the 250 million pounds of uranium contracted by world utilities in 2005.

It is true that the long-term uranium market and spot prices have a tendency to move together, because of "market-related" price mechanisms built in long-term contracts, and the fact that long-term contracts have quantity flexibilities built in them [25]. However, as Gene Clark, formerly with the US Department of Energy, said in an interview for UraniumSeek, a lack of liquidity and sophisticated market mechanisms remain features of the global uranium market [25].

It remains to be seen whether the emergence of trading mechanisms that we have seen in other markets (coal and iron ore come to mind) will extend to the uranium market. In 2007, the New York Mercantile Exchange signed a 10-year agreement with UX Consulting Company, to introduce U_3O_8 swap futures on CME and NYMEX platforms [27].

As of 2006, the 6 biggest uranium mining companies occupied 77% of the global market (Areva-17%, Cameco-16%, Rio Tinto-16%, Kazatoprom-13%, ARMZ/Rosatom-9%, and BHP Billiton-6%) [28]. In 2011, 4 countries contributed 72% of global uranium production (see Figure 2). Therefore, on the one hand, this indicates that the global uranium market is relatively concentrated.

However, two characteristics of this global market deserve further attention. First, the uranium market has neither a liquid spot market nor a producer's organization (its 1970s cartel having been disbanded), it is relatively fragmented geographically, and the largest producer of uranium really only emerged within the last decade. So on the other hand, the global uranium market is a thinly institutionalized market. Second, while the purpose of this paper is not to delve in the technical details of nuclear fuel production, suffice it to say that uranium is an unusual commodity in that it necessitates highly capital-intensive transformations (enrichment) prior to being used as fuel, a step that can be (and often is) conducted in a different country than the country of uranium ore extraction (see Table 1), and a step that is closely related to security issues. China does possess enrichment capabilities, so it mainly only needs uranium ore, but this still complicates the picture further.

Perhaps because of historical security concerns, and the absence of a widely used spot market, the global uranium market also remains a market where state-to-state relations continue to play an important role. Some recent major developments in Chinese procurement contracts were the result of state-to-state negotiations, including, recently, with the Canadian Government (more details below). The fact that China has ongoing long-term relationships with its close neighbours in Central Asia, such as with Kazakhstan and Uzbekistan, has also played a part in its ability to sign procurement agreements with them.

3. China's Projected Uranium Demand and Procurement Strategy

3.1. Current Needs and Supply-Demand Gap. Whereas a key dimension of China's energy security aims [29] has been to rely as much as possible on domestic production [30], more recently, an emphasis on rapid expansion of electricity production, diversification of the energy mix, as well as environmental protection has contributed to the emergence of China as a civilian nuclear power [31–33]. In 1991, China connected its first nuclear reactor to the electricity grid [34]. In 2002, only 2 nuclear reactors had been built in China, but the country was already firmly looking ahead towards a future where nuclear energy would produce between 40 and 80 GW [31]. "During the 10th 5 Year Plan (2001–2005) period, the key part of China's energy policy [was] to 'guarantee energy security, optimize energy mix, improve energy efficiency, protect ecological environment, continue to open up wider, and speed up the development of the west regions' [sic]." [31].

Five days after the earthquake and tsunami, the State Council suspended approval of new nuclear projects and started conducting comprehensive safety inspections of all nuclear projects. However, if there were any doubts as to whether China would continue to go ahead with its ambitious

Table 1: Top 5 exporters of uranium ore, natural uranium, and enriched uranium between 2008 and 2011.

(a)

Top 5 exporters of uranium and thorium ores (2008–2011)	Trade value in USD	Top 5 exporters of natural uranium and its compounds (2008–2011)	Trade value in USD
Namibia	$2,803,841,482	Canada	$7,152,512,173
Niger	$1,549,622,598	USA	$2,578,682,476
Australia	$1,152,033,863	France	$2,568,788,240
Malawi	$243,107,642	Kazakhstan	$1,593,772,641
United Kingdom	$17,024,333	Russian Federation	$322,983,583
Total world	$5,777,745,980	Total world	$15,131,504,216

(b)

Top 5 exporters of enriched uranium (2008–2011)	Trade value in USD
France	$10,755,771,990
USA	$5,493,937,151
Germany	$4,016,817,724
Netherlands	$3,631,753,994
China	$305,168,764
Total world	$24,623,102,401

Source: UN Comtrade.

Table 2: The 8 biggest civilian nuclear powers: planned reactors and uranium requirements in 2012.

Country	Reactors operable	Reactors under construction	Reactors planned and proposed within 15 years	Uranium requirements in 2012 (Tonnes U)
China	15	26	171	6 550
France	58	1	2	9 254
Japan	51	2	15	4 636
Russia	33	10	41	5 488
South Korea	23	3	6	3 967
Ukraine	15	0	13	2 348
United Kingdom	17	0	13	2 096
United States	104	1	30	19 724
World	435	62	489	67 990

Source: World Nuclear Association, April 2012.

civilian nuclear program following the Fukushima disaster and the year-long safety review, these doubts were dispelled early this year. In his speech for the Nuclear Security Summit in Seoul in March 2012, President Hu Jintao underlined the "irreplaceable role of nuclear energy in ensuring energy security and climate change" [35]. This was a signal that echoed Wen Jiabao's comments made a couple of months earlier in Abu Dhabi, where he said that "Nuclear power is a safe, reliable, mature technology providing clean energy. The safe and efficient development of nuclear power is the solution to future energy supply strategy." [36].

Then, "the former head of the NEA [National Energy administration] said that full-scale construction of nuclear plants would resume in March 2012" [37]. This confirmed that China is going ahead with its extensive expansion of civilian nuclear power plant program, albeit potentially at a slower rate: the target set by the National Development and Reform Commission (NDRC) in 2007 to have 40 GWe (Gigawatt-electric) online by 2020 [38] was upgraded to 70–80 GWe in 2010 and revised to 60–70 GWe in the aftermath of the Fukushima accident [37]. Currently at least 27 reactors are under construction [36] (or 26, according to the World Nuclear Association, see Table 2) and 50 more are planned according to the China Nuclear Energy Association [7].

As a consequence, whereas China's share of the market is still relatively low, planned construction of nuclear power plants is ambitious and China may be the first ranked importer of uranium globally by 2020. Qian Zhimin (China National Energy Administration) argued that by 2020, nuclear power could be contributing 7%-8% of China's energy needs, a higher rate than the official government target of 5% [39].

Table 3: Natural uranium production in 2010, compared with 2009 (tons of uranium).

Country	Production 2011 (tU)	Production 2010 (tU)	Production 2009 (tU)	Share in 2011 (%)	Share in 2010 (%)	Share in 2009 (%)	Change 2011/2009 (%)
Kazakhstan	19 451	17 803	14 020	36%	33%	28%	39%
Canada	9 145	9 783	10 173	17%	18%	20%	–10%
Australia	5 983	5 900	7 982	15%	11%	16%	–25%
Niger	4 351	4 198	3 243	8%	8%	6%	34%
Namibia	3 258	4 496	4 626	6%	8%	9%	–3%
Uzbekistan	3 000	2 400	2 429	6%	4%	5%	24%
Russia	2 993	3 562	3 564	6%	7%	7%	–16%
USA	1 537	1 660	1 453	3%	3%	3%	6%
China	1 500	827	750	3%	2%	1%	100%
Ukraine	890	850	840	2%	2%	2%	6%
Malawi	846	670	104	2%	1%	0%	713%
South Africa	582	583	563	1%	1%	1%	3%
Others	1 074	931	1 025	2%	2%	2%	5%
Total	54 610	53 663	50 772				8%

Source: Euratom Supply Agency, World Nuclear Association.

But such an ambitious civilian nuclear program coupled with very limited Chinese uranium reserves will only exacerbate China's import dependency ratio in this area, which is already high. As emphasized by Xiao Xinjian in China Energy, China has no choice but to develop a strong foreign procurement strategy in light of the country's poor uranium resources [40].

China's known uranium resources are insufficient: China total possesses at most 1 percent of the world's known recoverable uranium resources or about 68,000 tons [41]. The country's uranium output in 2011 was only 1500 tons (about 3% of global production, see Table 3), while its annual consumption had been at around 4,500 tons up to 2012 (or about 2% of global consumption) [42]. Its output is expected to eventually rise to 2,500 tons a year according to UX Consulting [7], but the quality of China's uranium resources is poor [43]. Clearly though, additional supplies are required and increasing dependence on imports is unavoidable in light of current development plans. China's imports may rise to about 17% of global consumption, or about 40,000 tons every year by 2020 [44].

Presumably in anticipation of a rapid increase in its uranium demand, China is already importing more uranium than it needs in a given year. For instance, China Daily indicated that China imported 17,135 tons of uranium in 2010, and 16,126 tons in 2011, according to the Chinese Customs [7], more than triple the amount in 2009.

3.2. Domestic Challenges. At the Chinese domestic level, many institutions with widely varying responsibilities are charged with ensuring nuclear safety, but these institutions all have different mandates and pursue different objectives. Similarly, at the regulatory level, a set of independent agencies exists, and this can create overlap issues. In addition, there remains work to be done on the level of the human capital needed to ensure the safety of the civilian nuclear program.

Hu Jintao emphasized this in his March 26th speech in Seoul: "we should establish and improve nuclear safety legal and regulatory system, strengthen the building of a nuclear emergency team, increase investment in research, staff training, and provide an institutional guarantee for strengthening nuclear safety, in response to the emergency mechanism to protect, and provide technical support to raise the level of nuclear safety human resources and support to enhance nuclear safety" [35].

These efforts, while enhanced since the Fukushima disaster, were built on earlier commitments to nuclear safety. In 2006 Kadak argued that

> *"China has developed top-level nuclear safety regulations on site location, safety in design, operations, and quality assurance. They annually set up inspection plans for each power station which focus on key areas of the regulations to assure compliance. They also have special inspections and reviews based on events that may occur at the plant. While the organizational framework is quite similar to the U.S. system, the intrusiveness of the regulator in day-to-day operations is not. The onsite inspectors follow the overall plans for inspections but are not as involved in day-to-day oversight of normal operations and outages. (...) Chinese regulatory personnel do perform inspections and oversee major activities during outages, however.*
>
> *(...) The Chinese government has made it quite clear that they will not tolerate injuries or radiation release. Given the power of the Chinese government, this clarity in expectations of the regulator and the government makes operational decisions of the plant very safety-focused. The challenge is for management to reinforce these*

> *expectations to all plant employees and contractors to be sure that no unsafe conditions exist [32].*

In recent years—and this trend has been compounded by the Fukushima disaster—we have seen the rise of another domestic challenge for the government in China, that of increased public awareness of the risks involved with nuclear power. This increased awareness, coupled with better access to information and means to express opposition via the Internet, has produced much activity online. A case in point is the opposition to the Gaozuang power plant in Nanyang, Henan province [45].

Despite domestic challenges, China has been able up to now to forge ahead with its national nuclear energy plan (as we have seen, albeit at a somewhat slower pace following the Fukushima disaster).

This has much to do with the fact that the Chinese nuclear industry is centralized domestically. Indeed, the civilian nuclear industry and the uranium mining industry are overwhelmingly controlled by two state-owned enterprises—China National Nuclear Corporation and China Guangdong Nuclear Corporation—that report directly to the State Council [41]. The structure of the domestic uranium market might therefore have afforded the Chinese government a stronger hand in fulfilling its policy goals (contrary to other more fragmented markets, such as iron ore, where the government has struggled). This may have allowed China more room for maneuver to concentrate on fulfilling its procurement strategy abroad.

3.3. International Challenges. Chinese companies also face challenges in fulfilling their uranium procurement needs internationally. This point was emphasized by Xie Qingxia, Hua-ming, and Wu Ping in their 2011 China Mining Magazine article [46]. The authors say that challenges lie in the form of a dearth of experience in the management of global uranium extraction companies, lack of knowledge in the legislation and domestic policies of foreign countries, the presence of political risks in host countries and the fact that China is a late player in the game.

In terms of political risks, besides possible diplomatic tensions, China must also manage potential issues to do with corruption and political instability with the source countries, including in Central Asia and Africa.

Further, because of the predicted excess of global demand over global supply in coming years, the Central Asian uranium market will remain very competitive. China is competing for access with Russia and India in Kazakhstan and Mongolia, while South Korea and Japan also buy significant amounts of uranium there and Iran is looking to raise its import as well. India is competing with China in Namibia and Niger as well. Thus, China is not operating alone in markets it is arguably the most comfortable in. Therefore, although China has been trying to diversify its supply sources and shown caution not to overbid for resource acquisition, in the end, strong competition has compelled it to make use of economic and diplomatic tools to gain an edge. Indeed, "the Chinese have shown they will often pay above market prices for those mines, companies and other assets that are genuinely rich in natural resources" [47]. In many ways, uranium market pressures continue to be resolved within a state-to-state framework.

Another type of political risk is the risk of falling afoul of domestic public opinion in source countries. This risk exists in developed source countries. For instance, the Australian population reticence towards nuclear power domestically and abroad has had an impact on the country's export capacity. Since the 1970s, the country has seen ongoing debates between the uranium mining and nuclear industry and environmentalists and indigenous land rights activists. Australia also suffers from other usual obstacles to uranium mining, including in the form of shortage of labour and infrastructure [48]. But it is Australia's 1984 "Three Mines Policy" [9] and subsequent "No New Mines" policy that really limited the scope of uranium mining in the country, until a recent, and timid, loosening.

Social opposition and resulting stricter environmental regulations are thus partly responsible for the transfer of uranium mining away from developed countries in recent years.

However, public opinion risks do not come exclusively from developed economies. Indeed, when it comes to planning investments in developing countries, Chinese companies need to successfully manage the public perception of their actions as well. Following the Fukushima incident, public opposition has risen in Kazakhstan, already exacerbated by years of environmental and safety mismanagement during the Soviet period. "The Chinese have apparently sought to decrease this risk by partnering with the state-owned Kazatomprom in exchange for equity in domestic facilities." [47].

This situation is not unlike that found in other commodity markets. Indeed, China was not a major stakeholder when global commodity market institutions emerged during the second half of the twentieth century and has found itself a newcomer in many markets as it rose to prominence in the past two decades. But in the case of uranium, the fact that the market does not have a producer's cartel, and was in need of investment and expansion as China entered the market, has given China more room to maneuver.

3.4. Procurement Strategy. China has been basing its uranium procurement strategy on the national "Two markets, Two resources" policy, coined in the 1990s, which works to develop both domestic supply sources (this includes developing advanced nuclear power systems and/or alternative nuclear power methods to save fuel) and international supply sources (through foreign acquisition, investment as well as long-term contracts). "By 2020, 1/3 of China's supply of natural uranium will come from domestic uranium production, 1/3 from direct procurement from foreign suppliers, and 1/3 from the overseas holdings of uranium production." [46]. Such a diversified strategy can spread the risk associated with a high import dependency ratio.

Therefore, on the one hand, China is increasing its uranium production domestically (see Table 3). On the other hand, as part of the "Going Out" strategy (which fits under the "Two Markets, Two Resources" policy), China is taking steps to acquire uranium resources internationally. It has equity in Niger and Kazakhstan mines, is investigating Uzbekistan, Mongolia, Namibia, Algeria, and Zimbabwe, and other sources are progressively being added. A bilateral safeguards agreement will also allow imports from Australia, and more recently, Canada.

Beijing is also using creative ways to engineer procurement contracts. As mentioned above, in November 2006, two Chinese firms have established a joint venture with Kazakhstan's state-owned Kazatomprom in a uranium mining project (49 percent stake), in exchange for stakes in either Chinese nuclear power plants or fuel reprocessing facilities for Kazatomprom [49]. China has also "provided interest-free soft loans to the governments of Uzbekistan, Niger and other uranium-rich countries (World Nuclear News, June 10, 2010; November 4, 2008; Reuters, April 24, 2010)" [47].

We stand at the beginning of China's engagement with the global uranium market. China has thus an opportunity to learn from past experiences acquired while dealing with high import-dependency ratios in other types of commodities. Up to now, China has developed a multi-pronged strategy of engagement in the uranium market, that has allowed it to triple its total uranium imports, and forge ahead with the world's most ambitious civilian nuclear power development plan, all within the span of a few years.

4. Potential for International Cooperation

4.1. A Case in Point: Bilateral Cooperation between China and Canada

Uranium Ore. Uranium trade relations between Canada and China show that there remains a large state-to-state angle to this trade. Among the largest uranium producers, Canada has the highest-quality uranium. Indeed, "only Canada has a significant amount of ore above 1 percent—up to about 20 percent of the country's total reserves. In Australia, on the other hand, some 90 percent of uranium has a grade of less than 0.06 percent. Much of Kazakhstan's ore is less than 0.1 percent" [48]. While the Fukushima accident reduced demand for new nuclear power plants in the near-term, CAMECO has said it is sticking to its target to double uranium production to 40 million pounds by 2018. Canada's uranium production is projected to increase at an average rate of 9 per cent a year to 15 300 tonnes in 2016.

During the Canadian Prime Minister's visit to China in February 2012, a protocol amending Canada's nuclear cooperation agreement with China to allow the export of uranium concentrate was announced. This was big news both for China's energy security and potential to diversify supply sources, and Canada, which can now export uranium directly to China. These sales were banned up until now. In 1976, Canada barred exports of uranium and nuclear reactors to countries that had not signed the Non-Proliferation Treaty (China signed in 1992). A 1994 agreement allowed the sale of reactors, but until last year's amendment to that pact, Canada hadn't yet relaxed its restriction on selling nuclear fuel to China. So until last year, Cameco Corp. had to ship the uranium that it was selling to China from other countries, such as Namibia and Kazakhstan.

In November 2011, Cameco signed an agreement with China Guangdong Nuclear Power Holding to import 29,000 tons of the mineral through 2025. Canada's Cameco has also contracted to sell 23,000 tons of uranium concentrate trough 2020 to China Nuclear Energy Industry Corporation (directly owned by China National Nuclear Corporation) [44].

Following this, Saskatchewan Minister of Energy Bill Boyd signed a Memorandum of Understanding (MOU) in February 2012, on scientific and technical research co-operation on uranium geology with the Beijing Research Institute of Uranium Geology, a research establishment of the China National Nuclear Corporation.

Cameco Corp. Chief Executive Officer Tim Gitzel said "China is becoming the leader of the world" for nuclear energy [50]. Gitzel said Cameco continues to discuss partnerships with Chinese companies on the possibility of jointly developing uranium projects in China, Canada, and other countries.

4.2. Technology. This relationship extends to technical levels of cooperation as well. Indeed, technological cooperation in civilian nuclear technology has occurred between Canada and China in recent years. Indeed, in 2009, the capacity of CANDU's heavy water reactors to reuse spent fuel recycled from other light water reactors was explicitly recognized by a panel appointed by the China National Nuclear Corporation. It "cited the design's 'enhanced safety and good economics' as reasons it could be deployed in China in the near term" [51] and recommended that two units be built.

China is also pursuing reprocessing capabilities in partnership with Canadian CANDU designer Atomic Energy of Canada. China has built two CANDU reactors (and is considering building additional units), which are utilizing reprocessed fuel from its nine light water reactors. CANDU reactors can also run on thorium fuel, and China has been working on developing a thorium fuel cycle with its Canadian partners. Thorium is more abundant in China, cheaper to mine, produces less waste and, if successful, will enhance Chinese energy security.

As the case of Canada-China uranium and nuclear relationship shows, the uranium trade is nested within a thicker web of state-to-state relations that include safety and technological exchange issues. As will be developed further below, this embeddedness may have a positive impact on the nature of China's participation in the global uranium market [52, 53].

4.3. Cooperation on the Enrichment Level. Uranium being only the first step towards the development of nuclear fuel, cooperation initiatives regarding enriched fuel also play a role in the broader civilian nuclear fuel market. The World Nuclear Association lists operating uranium enrichment facilities in 11 countries, 6 with large capacity (France, the US, the UK, Germany, Russia and the Netherlands) and 5 of smaller capacity (China, Japan, Brazil, Pakistan, and Iran) [54].

There are multiple initiatives underway which seek to coordinate enrichment activities worldwide, and the International Atomic Energy Agency (IAEA) actively encourages these "Multilateral Nuclear Approaches" [54]. These programs contribute to enhancing the global tracking of enriched fuel, and thus fulfill nonproliferation goals, while facilitating the coordination of the global market for enriched fuel. A case in point is the Eurodif enrichment center in France, jointly owned by five countries (France, Belgium, Italy, Spain, and Iran), operating under the IAEA oversight, and giving the participants some controlled access to the final product without sharing any technology [54].

Similar initiatives are underway in Russia, where under the IAEA's supervision, an International Uranium Enrichment Centre is being created in Siberia, with Russian, Kazakh, Ukrainian, and Armenian equity. Other such projects are underway in the US, the UK, the Netherlands, and Germany.

The IAEA is also calling for the establishment of international banks of enriched fuel. A deal was signed for Russia to make available 120 tons of nuclear fuel, and a similar arrangement was being discussed with Kazakhstan in 2010. Such initiatives, say former IAEA Director General Mohamed ElBaradei, "make sure that every country that is a bona fide user of nuclear energy, and that is fulfilling its nonproliferation obligations, is getting fuel" [48].

This only goes to show that uranium procurement is a part of broader civilian nuclear issues. China has displayed willingness to collaborate on security issues that pertain to civilian nuclear programs and nonproliferation, and additional participation in a global cooperation mechanism on uranium enrichment would further cement China's role as a constructive participant in such multilateral initiatives.

4.4. Cooperation among Developing Countries. At the level of safety standards, China has indicated its willingness to play a leading role in fostering cooperation initiatives among developing countries. Indeed, the country has indicated that it is interested in providing nuclear safety assistance, and focuses on helping developing countries establish and improve their nuclear safety infrastructure, as well as improve nuclear safety and technical standards [35].

China has already been involved in multiple regional nuclear security training courses providing training to nearly 100 people from more than 10 countries in the Asia-Pacific region [35]. It also looks to help developing countries improve technical levels of nuclear safety.

This is yet another way in which the multidimensionality of the civilian nuclear industry manifests itself. China's engagement internationally in the realm of safety issues, and with developing countries (a setting where China has long played a role), may provide it with the experience and a platform to eventually broaden its engagement to other issues, for example, to issues of natural/enriched uranium procurement.

4.5. Impact of the Nuclear Security Summits. Enhanced cooperation on issues of nuclear security at an international level had already started with the Washington Nuclear Security Summit held in 2010, but the Fukushima accident brought back to the fore the need to enhance state capacity to cope with the unexpected and the need to address issues of nuclear safety.

Indeed, the second Nuclear Security Summit held in Seoul in March 2012 broadened its agenda to include nuclear safety and proved to be an important step following the Fukushima accident and the need to discuss this issue in a multilateral setting. There is much to learn from the Japanese accident, and China has shown its willingness to learn from this experience.

The summit is useful despite the fact that sovereignty concerns and economic and technological differences hinder the establishment of binding safety standards across the board. There are difficulties in harmonization of safety standards, but China has demonstrated a will to work in cooperation with other developed nations on this regard. It shows great confidence on China's behalf to fully engage developed countries in this sensitive issue.

"In July 2010 a 22-strong IAEA team from 15 countries carried out a two-week Integrated Regulatory Review Service mission to review of China's regulatory framework for nuclear safety. The IAEA made a number of recommendations but said that the review had provided 'confidence in the effectiveness of the Chinese safety regulatory system and the future safety of the vast expanding nuclear industry.'" [37]. China has also "requested and hosted 12 Operational Safety Review Team (OSART) missions from IAEA teams to October 2011" [37].

In the past years, China has made substantial efforts in this regard. China has also made relatively noticeable efforts in reaching out regarding nuclear safety, as it has done with the US (implemented in 1998 and reinforced in 2005 by a Memorandum of Understanding that granted Westinghouse the contract to build four commercial nuclear reactors in China). China is part and parcel of the international community and its efforts to enhance nuclear security and safety globally [16].

A case in point, China is a fully fledged member of the International Atomic Energy Agency, committed to international nonproliferation efforts and cooperating on issues of civilian nuclear technology with France (Areva), Canada (Atomic Energy of Canada—CANDU), and the US (Westinghouse) among others, as well as participating in related international frameworks.

China's energy needs are growing at such speeds that the parallel growth of its civilian nuclear program appears inevitable. But to do it, as President Hu Jintao emphasized in his Seoul speech, China needs to "face the risk of nuclear safety, to learn the lessons of the nuclear accident, and take effective measures to enhance security and reliability of nuclear energy, to promote the safety of nuclear energy, sustainable development" [35].

All in all, at the domestic level, a centralized industry, and at the international level, a geographically dispersed and uncoordinated market allowing some space for expansion have provided China with relatively comfortable conditions to roll out its procurement strategy abroad. But the fact that the uranium market remains one step away from nuclear security and safety issues, which have spawned a web of international cooperation initiatives, may foster a cooperative environment for uranium as well.

It remains that whereas the structure of the global uranium market have allowed China to carve itself a place and roll out its procurement policy, the safety and security dimensions of the nuclear industry have provided China with the opportunity for a cooperative and confident engagement at a multilateral level.

Many uncertainties remain, namely, the potential for a supply squeeze, delayed production due to mining accidents, and public opinion protests among others, so peaceful coexistence, or even cooperation, is not a foregone conclusion. Indeed, it remains to be seen whether a conceptual frontier will remain between natural uranium ore mining and enriched uranium production and other civilian nuclear issues. Further research could look at the likelihood of spilling effects. However, the particular conditions under which this market is evolving currently allow for such a possible development.

5. Conclusion

The first signs of China's likely future impact on the global uranium industry have already been felt. Despite China's uranium requirements being less than half than that of the US, China still imported almost as much uranium as the US did in 2010, three times more than the amount it imported in 2009. This is despite the fact that the US has over 100 reactors in operation, against China's 15.

Early signs also point to a reorganization of the global uranium market, with the emergence of new players such as Kazakhstan. This sudden increase and investment in Kazakhstan's uranium mining industry has contributed to the rise of this country to number one uranium producer in the world, whereas it was all but absent from global uranium trade in 2003 [19].

The answer as to why China has succeeded in establishing itself as a confident player pushing forward a multipronged international uranium procurement strategy has to do with both domestic and international variables. On the one hand, at the domestic level, the centralized structure of China's uranium procurement industry has allowed industry and government stakeholders to develop and implement a coherent strategy (contrary to the situation in the fragmented iron ore market for instance). On the other hand, at the international level, the absence of an exporters' cartel or oligopoly established before China's emergence as a large purchaser have enabled it to carve itself a place on the global market.

On the top of that, recent international cooperation initiatives, which encourage transparency and collaboration, even if they are concentrating on nuclear safety and security issues, have provided China with the opportunity for a cooperative and confident engagement. These international efforts have showcased China as a country ready to rise to the occasion and be a responsible player, including as a fully-fledged member of the International Atomic Energy Agency.

As the country builds confidence in dealing with these issues in an international setting, could it lead it to spearhead further initiatives, such as an international uranium demand management initiative, that could be managed through the Shanghai Cooperation Organization? China seeks to have a say in global market institutions, which for the most part have been created prior to its recent reemergence, that is commensurate to the share of the global demand that it now occupies. Demand management initiatives like this could be an area where there is room for China to innovate, perhaps in its own regional setting at first [55].

All in all, there is potential for peaceful coexistence—and even international cooperation—in the global uranium market, something towards which China can contribute meaningfully.

Acknowledgments

This paper constitutes a preliminary work of a larger research project by P. Massot on The Impact of China on Global Commodity Markets, funded by the Social Sciences and Humanities Research Council of Canada. Sincere thanks are given to Matthew Gravelle for his helpful comments on an earlier draft of this paper. The research of Z.-M. Chen has been supported by the Ministry of Education Foundation of China (no. 12YJCZH021). Some sections of this paper are built on an op-ed published in Chinese by P. Massot: "How can China deal with the dependence on imported uranium (Zhongguo ruhe yingdui haiwai you yilai)," China Business News Daily, April 23, 2012, A6, http://www.yicai.com/news/2012/04/1654156.html.

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Hindawi Publishing Corporation
The Scientific World Journal
Volume 2013, Article ID 415812, 9 pages
http://dx.doi.org/10.1155/2013/415812

Research Article

Emergy Analysis of Biogas Systems Based on Different Raw Materials

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Received 12 September 2012; Accepted 10 December 2012

Academic Editors: B. Chen and Z.-M. Chen

Environmental pollution and energy crisis restrict the development of China, and the utilization of renewable technology is an effective strategy to alleviate the damage. Biogas engineering has rapidly developed attributes to solve environmental problems and create a renewable energy product biogas. In this paper, two different biogas plants' materials were analyzed by emergy method. One of them is a biogas project whose degraded material is feces (BPF system), and the other is the one whose degraded material is corn straw (BPC system). As a result, the ecological-economic values of BPF and BPC are $28,300/yr and $8,100/yr, respectively. Considering currency, environment, and human inputs, both of the biogas projects have the ability of disposing waste and potential for development. The proportion of biogas output is much more than fertilizer output; so, fertilizer utilization should be emphasized in the future. In comparison, BPF is better than BPC in the aspects of ecological-economic benefits, environmental benefits, and sustainability. The reason is the difficulty of corn straw seasonal collection and degradation. Thus it is proposed that BPC should be combined with the other raw materials.

1. Introduction

China is the world's largest developing country with a population over than 1.3 billion. With the development of economy and industrialization, the problems of excessive energy consumption significantly affect the future of China. Finding new energy sources to replace fossil fuels is an urgent task for China [1–5]. Anaerobic digestion is one of the most appropriate technologies to solve these problems. There are large biomass resources in China, especially crop straw, forest residue, livestock and poultry manure, and various kinds of municipal and industrial organic wastes and waste water [2]. Such sufficient materials promote the development of biogas, especially the large-and medium-sized biogas projects.

In 2003, the "agricultural ecological" program was carried out, which created a favorable condition for the development of biogas projects. According to statistics (shown in Figure 1), biogas yield in 2009 is 1.75 times more than 2003. In addition, the development of biogas projects also positively influences related industries, such as processing manufacturing, construction materials, and construction engineering. All of them have achieved good economic, social, and other comprehensive benefits [6].

With the number of biogas projects increasing, biogas ecological systems have attracted more and more attention. Biogas ecological system is a complexity composed of agricultural, environment, energy, society, and other relevant sectors. The aims of a biogas ecological system are producing an energy carrier from renewable resources and achieving multiple environmental benefits. Some research has been taken on biogas ecological systems, but mostly, the focus have been on the technical evaluation, economic benefit, and energy flows [7–13]. The research methods of assessing biogas ecological system include exergy accounting, energy analysis, life cycle assessment, and emergy analysis which have been developed in the last 30 years. Emergy is chosen in this paper because it is a particularly appropriate tool to evaluate the agricultural production system. Emergy focuses on the compound ecosystem at the interface between natural and human systems, which involves many subject areas, not only the systems of ecology, ecosystem ecology, energetic, resource science, environmental science, systematic, earth

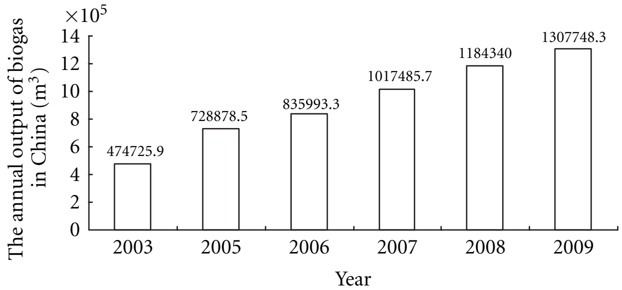

Figure 1: Bar chart of the number of biogas projects in China.

science, and other natural sciences, but also those relating to economics, sociology, forecasting and the other humanities [14, 15]. Emergy method unifies all the measures, and the whole inputs indices along the forming process are converted into solar emergy (sej) and solar transformation (sej/J). So, both the environmental values and the economic values can be calculated, which simplifies the assessment process.

All the research mentioned earlier is focused on one kind of biogas plant, and the material used as input is not differentiated. However, with the development of biogas technology, there are several biogas materials species. At present, the main anaerobic fermentation materials are straw and feces, and their fermentation process and parameters (temperature, concentration, refluxing ratio, stir mode, etc.) are very different. Therefore, only by considering the different characters of materials, biogas project system analysis could be comprehensive and correct. In this paper, two representative biogas projects are chosen to be compared, and emergy is used to analyze their characteristics. The aim of this study is to assess the ecological-economic benefit, environmental benefit, and sustainable development capability of two different raw materials (corn straw and feces) in the biogas generation system and lay a theoretical foundation for the generalization of the ecological biogas production system. All the calculations aim to be as transparent as possible in order to make the results useful for future analyses.

2. Materials and Methods

2.1. Study Site. The two biogas projects studied in this paper are different in degraded materials; one is corn straw, and the other is feces. All the data come from the results of site investigation among the whole year.

2.1.1. BPF System. The biogas project, where degraded material is feces (BPF), is located in the west of Hegezhuang village of Chaoyang district in Beijing. The total investment of biogas plant is RMB 2,600,000 Yuan, occupying 2930 m^2. BPF began operating in October of 2010, processing feces from three villages, Naidong, Hegezhuang, and Naixi. This biogas project solved the problem of feces pollution and improved the quality of village life.

The technology of BPF is continuous stirred tank reactor (CSTR), and the material of the tank is enameled pressed steel. The capacity of the BPF is 400 m^3, which has a liquid-gas storage integrated tank, including 224 m^3 liquid storage volume and 200 m^3 gas storage volumes. The biogas project can digest 10~20 t solid manure and 25 t domestic sewage per day, and its biogas yield is 650 m^3/d. In routine management, the fermented concentration is maintained to 6%~10% by the way of biogas slurry refluxing. A solar system is one of the most important parts of the whole biogas plant, because it can increase feeding materials temperature to 5°C in winter. Moreover, some of the output biogas is heated to maintain fermented temperature. In spring and autumn, 250 m^3 biogas will be heated, and the output is 400 m^3. In summer, because of high temperature, it is not necessary to heat the biogas tank; so, the entire biogas of 650 m^3 will be exported. In winter, there is 350 m^3 biogas heated and 300 m^3 biogas exported. In addition, 113 kg coal will be supplied per day in winter which will last for 4 months; so, the quantity of the coal is 13.6 t/yr.

2.1.2. BPC System. The other biogas project, where degraded material is BPC, is located in the Dongyaozhuang village of Qing country in Hebei province, where crop planting industry is well developed. Because of this, there are a number of types of waste crops straw stalks, and the environment has been polluted by stacking and willfully burning straws. In 1999, the first 1000 m^3 CSTR biogas underground tank was built. However, during that period, the technology was immature; so, the biogas tank could not be put into operation. After that, a brick-concrete structure biogas tank of 400 m^3 was constructed successfully in 2005, which was the first in China. However, due to limitations of building materials and technology, that biogas project is out of service now. Through summarizing construction operation experiences and improving technology, the new biogas tank of 400 m^3 was constructed in 2006. By debugging and running, it was in formal operation in 2007 and has become the star exemplary biogas project in China.

The technology of BPC is up-flow solids reactor (USR), and the material of the tank is welded steel plate. The whole volume of BPC is 400 m^3, with treatment capacity of 900 kg corn straw every day. To maintain the feeding concentration, 2~3 t water should be added per day. The fermentation temperature is 44~55°C, and the biogas production capacity is 480 m^3/d. The whole biogas system needs 200 m^3 of biogas heated per day in winter and 120 m^3/d in spring and autumn. The biogas net output amount is 280 m^3/d in winter and 360 m^3/d in spring and autumn. Because it is not necessary to heat it, the biogas net output amount is 470 m^3/d in summer. The same as BPF, 150 kg/d coal is used to heat the biogas tank which lasts about 4 months, and the amount of coal is 18 t/yr.

2.2. Emergy Accounting. The input and output raw data of the two biogas systems are recorded for the whole year of 2011. The details of emergy accounting can be referred to through the works of Odum [16]. The process of emergy accounting consists of two steps. The first is to define the boundary of the system and then make emergy evaluation tabulation. The next step is to sum all the emergy contributions from the

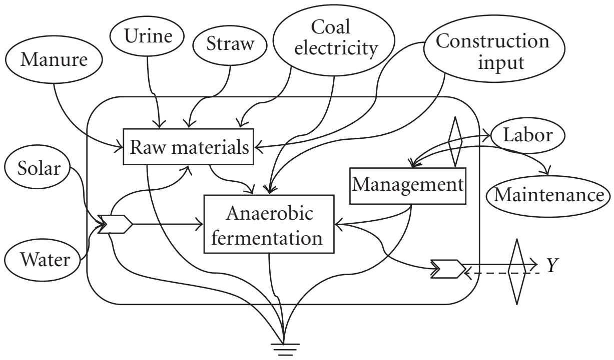

Figure 2: Emergy system diagram of the biogas project.

independent inputs and biogas systems evaluation as shown in the established emergy indicator framework.

The emergy system is shown in Figure 2. Input resource is divided into three parts: free local renewable resources (RRs) embracing raw materials (feces/corn straw), solar energy, and underground watering, renewable purchased (RP) inputs includes human labor, and nonrenewable purchased (NP) inputs covering construction inputs, coal and electricity. All the products including biogas and biogas residues are system yield (Y). In the counting process, the whole economic values are converted into solar emergy (sej). And then solar emergy turns into emergy-monetary value (Em$) through an emergy-monetary ratio. In this paper, emergy-monetary value (Em$) represents not only macroeconomy value of emergy flow, but also ecological-economic value, which assesses the eco-efficiency, environmental impact, and the sustainable capacity of the system.

2.3. Emergy Evaluation Index. To analyze these two types of biogas systems for the aspects of ecological-economic benefit, environmental benefit, and sustainable development ability, ten evaluation indices are applied in this paper.

2.3.1. Purchase Emergy Ratio (PER). It is a ratio of input emergy social economy feedback and total input emergy. It depends on system's dependent degree to external resources.

2.3.2. Natural Emergy/Purchase Emergy. This ratio is the emergy from natural resources divided by input emergy social economy feedback, which shows the condition of industrial competitiveness.

2.3.3. Emergy Investment Ratio (EIR). It's a ratio of input emergy social economy feedback and input emergy of natural resources, which shows the cost of the system.

2.3.4. Emergy Yield Ratio (EYR). It is a ratio of the total output emergy and input emergy social economy feedback, which represents the situation of the system production.

2.3.5. Emergy Self-Sufficiency Ratio (ESR). ESR shows the self-maintenance ability of the system. It is the emergy from nature divided by the total output emergy of the system.

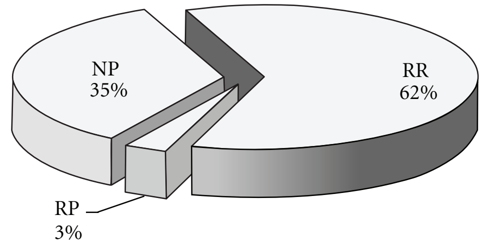

Figure 3: Emergy input ratio of BPC.

2.3.6. Ratio of Waste Treatment (%W). It is a ratio of the emergy of waste (for a biogas project, it means the raw materials, such as corn straw and feces) treatment and the total output emergy of the system. This value shows the ability of the treatment of waste of the whole system.

2.3.7. Environmental Loading Ratio (ELR). This is an important index of environment, [which means the pressure to environment from the system.] It is equal to the ratio of total nonrenewable emergy divided by renewable emergy.

2.3.8. Feedback Yield Ratio (FYR). This ratio means the emergy of system self-feedback (for biogas system, it is the part of biogas that is heated) divided by economy feedback emergy, which shows the self-organizing ability of the system.

2.3.9. Renewable Ratio (%R). It is a ratio of renewable emergy and input emergy of the system, which means the system's renewable property.

2.3.10. Emergy Sustainability Ratio (ESR). This evaluation index shows the situation of the system sustainability, which is equal to EYR divided by ELR.

3. Results and Discussion

3.1. Emergy Accounting. As shown in Table 1, the total emergy input of the BPC system amounts to 2.07×10^{17} sej/yr, of which the RR, RP and NP contribute 62%, 3%, and 35%, respectively (shown in Figure 3). The emergy yield of the biogas system consists of biogas and biogas residues, and the biogas residues consist of three parts: nitrogen fertilizer, phosphate fertilizer, and potash fertilizer. As shown in Figure 4, biogas is the most important production, the yield of which amounts to 6.92×10^{17} sej/yr and makes up 99% of the total emergy yield. The part of the biogas residues is only 1%.

Based on the data in Table 2, the total emergy input of BPF system amounts to 6.42×10^{17} sej/yr, of which RR, RP, and NP contribute 88%, 1%, and 11%, respectively (Figure 5). As to RR, solid manure and urine (including flushing sewage) account for 46.50% and 53.50%, respectively. The same as BPC system, the emergy yield of the biogas system also consists of biogas and biogas residues. As shown in Figure 6, biogas is the most important production, the yield of which

Table 1: Energy accounting for BPC system.

No.	Item[a]	Units	Raw date	Transformity (sej/unit)	References	Solar emergy (sej/yr)	Em ($)
	Local renewable resources						
1	Underground water	J	3.65*E* + 09	4.10*E* + 04	Odum, 1996 [16]	1.50*E* + 14	0
2	Corn straw	J	4.72*E* + 12	2.70*E* + 04	Odum, 1996 [16]	1.27*E* + 17	3180
	Total (RR)					1.28*E* + 17	3180
	Renewable purchased inputs						
3	Human labor	J	1.84*E* + 10	3.80*E* + 05	Xi and Qin, 2006 [17]	6.99*E* + 15	5804
	Total (RP)					6.99*E* + 15	5804
	Nonrenewable purchased inputs						
4	Steel plate[b]	US $	1.75*E* + 06	1.40*E* + 09	Brown and Ulgiati, 2004 [18]	2.45*E* + 15	846
5	Equipments, PE pipes[b]	US $	5.44*E* + 03	4.94*E* + 12	Brown and Ulgiati, 2004 [18]	2.69*E* + 16	5441
6	Civil work cost[b]	US $	6.05*E* + 02	4.94*E* + 12	Xi and Qin, 2006 [17]	2.99*E* + 15	605
7	Maintenance cost	US $	6.05*E* + 02	4.94*E* + 12	Xi and Qin, 2006 [17]	2.99*E* + 15	605
8	Coal	J	4.82*E* + 11	4.00*E* + 04	Odum, 1996 [16]	1.93*E* + 16	2177
9	Electricity	J	1.08*E* + 11	1.59*E* + 05	Xi and Qin, 2006 [17]	1.72*E* + 16	1886
10	Protein powder	US $	9.27*E* + 01	4.94*E* + 12	Xi and Qin, 2006 [17]	4.58*E* + 14	931
	Total (NP)					7.22*E* + 16	12491
	Total input					2.07*E* + 17	21475
	System feedback						
11	Biogas (heated)	J	8.28*E* + 11	2.48*E* + 05	Bastianoni and Marchettini, 2000 [15]	2.05*E* + 17	7666
	Total (F)					2.05*E* + 17	7666
	Yield						
12	Biogas (output)	J	2.79*E* + 12	2.48*E* + 05	Bastianoni and Marchettini, 2000 [15]	6.92*E* + 17	28996
13	Nitrogen fertilizer	g	6.58*E* + 05	4.62*E* + 09	Zhang et al., 2005 [19]	3.04*E* + 15	145
14	Phosphate fertilizer	g	3.29*E* + 05	1.78*E* + 10	Zhang et al., 2005 [19]	5.86*E* + 15	218
15	Potash fertilizer	g	4.94*E* + 05	2.96*E* + 09	Zhang et al., 2005 [19]	1.46*E* + 15	193
	Total yield (Y)					7.02*E* + 17	29553

[a] Local nonrenewable resources can be neglected.
[b] Items have been divided by a lifetime of 20 years.

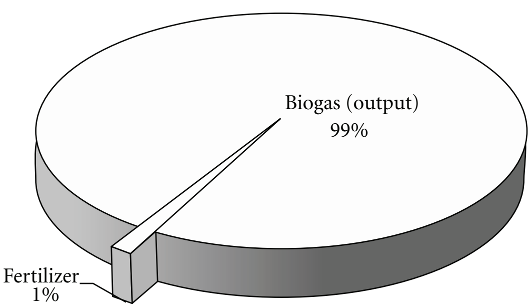

Figure 4: Emergy output ratio of BPC.

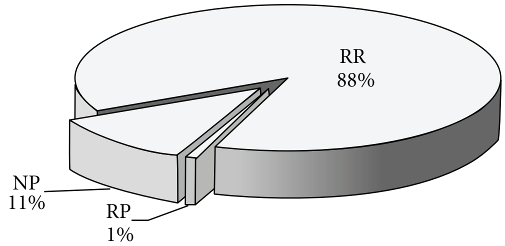

Figure 5: Emergy input ratio of BPF.

amounts to 8.16×10^{17} sej/yr and makes up 75% of the total emergy yield. The remaining part of the biogas residues is divided into three parts: nitrogen fertilizer (3%), phosphate fertilizer (17%), and potash fertilizer (5%).

In comparison to BPC system, the input emergy of BPF system is 4.38×10^{17} sej/yr more than BPC, because RR is a large proportion of BPF system. Otherwise, as to output emergy of BPC system, biogas output is 99%, and biogas manure is 1%; concerning output emergy of BPF system, biogas output is 75%, and biogas manure is 25%. The reason is the difference of the nature of digestion materials, construction scale, and digestion technology. For the BPC system, the greatest goal is biogas production; so, we call this kind of biogas project energy-ecology type. On the other hand, BPF system realizes the target of dealing with manure

Table 2: Energy accounting for BPF system.

No.	Item[a]	Units	Raw date	Transformity (sej/unit)	References	Solar emergy (sej/yr)	Em ($)
	Local renewable resources						
1	Sunlight	J	1.26E + 11	1.00E + 00	Odum, 1996 [16]	1.26E + 11	0
2	Solid manure	J	9.76E + 12	2.70E + 04	Odum, 1996 [16]	2.64E + 17	0
3	Feces	J	7.98E + 10	3.80E + 06	Odum, 1996 [16]	3.03E + 17	0
	Total (RR)					5.67E + 17	0
	Renewable purchased inputs						
4	Human labor	J	1.38E + 10	3.80E + 05	Xi and Qin, 2006 [17]	5.24E + 15	4353
	Total (RP)					5.24E + 15	4353
	Nonrenewable purchased inputs						
5	Civil work cost[b]	US $	2.96E + 03	4.94E + 12	Xi and Qin, 2006 [17]	1.46E + 16	2963
6	Equipments, PE pipes[b]	US $	5.20E + 03	4.94E + 12	Xi and Qin, 2006 [17]	2.57E + 16	5200
7	Appurtenant work[b]	US $	7.10E + 02	4.94E + 12	Xi and Qin, 2006 [17]	3.51E + 15	713
8	Maintenance cost	US $	6.05E + 02	4.94E + 12	Xi and Qin, 2006 [17]	2.99E + 15	605
9	Coal	J	3.64E + 11	4.00E + 04	Odum, 1996 [16]	1.46E + 16	738
10	Electricity	J	7.28E + 10	1.59E + 05	Xi and Qin, 2006 [17]	1.16E + 16	1173
	Total (NP)					7.29E + 16	11391
	Total input					6.45E + 17	15744
	System feedback						
11	Biogas (heated)	J	1.60E + 12	2.48E + 05	Bastianoni and Marchettini, 2000 [15]	3.97E + 17	13881
	Total (F)					3.97E + 17	13881
	Yield						
12	Biogas (output)	J	3.29E + 12	2.48E + 05	Bastianoni and Marchettini, 2000 [15]	8.16E + 17	28561
13	Nitrogen fertilizer	g	8.63E + 06	4.62E + 09	Zhang et al., 2005 [19]	3.99E + 16	1838
14	Phosphate fertilizer	g	1.02E + 07	1.78E + 10	Zhang et al., 2005 [19]	1.82E + 17	6844
15	Potash fertilizer	g	1.73E + 07	2.96E + 09	Zhang et al., 2005 [19]	5.12E + 16	6796
	Total yield (Y)					1.09E + 18	44039

[a] Local nonrenewable resources can be neglected.
[b] Items have been divided by a lifetime of 20 years.

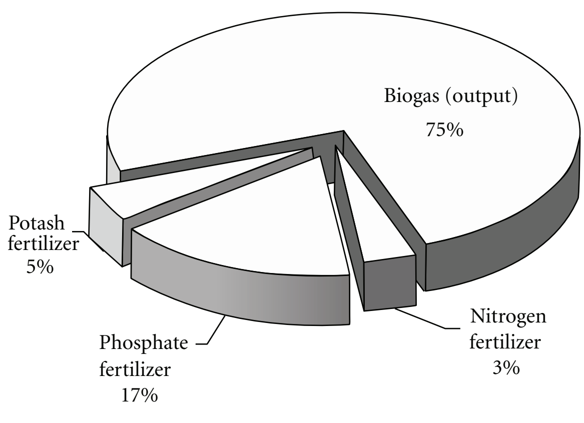

Figure 6: Emergy output ratio of BPF.

and wastewater efficiently, which is inclined to the energy-environmental type.

3.2. Ecological-Economic Analysis. A biogas project is one of the circular agriculture ecology patterns dealing with agricultural wastes, and the ecological-economic benefits could be measured by emergy-monetary value, which is a specific form of emergy-monetary value reflected in the economic market.

In Table 3, the total investment funds of BPF and BPC are $15,700/yr and $21,500/yr, respectively. The BPF resources (feces) do not need to be bought; so, investment funds of the BPF system include RP and NP, but those of BPC system include RR, RP, and NP. Thus, the BPF system can alleviate the government pressure and be worthy of widely promotion. In contrast, the BPC resources (corn straw) need to be bought, because of its extensive application, such as fuel to heat water and briquetting forming fuel. In addition, straw must be crushed before anaerobic digestion. And supplementary additives, such as protein powder, are required in the anaerobic digestion process. So, the RP and NP of the BPC system are both higher than those of the BPF. Moreover, the BPF system has solar heating system which decreases the quantity of coal and electricity; so, the whole input energy is less than BPC.

The outputs of BPF and BPC system are $44,000/yr and $29,600/yr, respectively. The main reason is the large gap of output economic value of biogas residues, which causes

Table 3: Table of emergy monetary value \$/yr.

Item	BPC	BPF
RR	3.18×10^3	/
RP	5.80×10^3	4.35×10^3
NP	1.25×10^4	1.14×10^4
Total input	2.15×10^4	1.57×10^4
Biogas (output)	2.90×10^4	2.86×10^4
Nitrogen fertilizer	1.45×10^2	1.84×10^3
Phosphate fertilizer	2.18×10^2	6.84×10^3
Potash fertilizer	1.93×10^2	6.80×10^3
Total yield	2.96×10^4	4.40×10^4
Ecological-economic value	0.81×10^4	2.83×10^4

differences between the two biogas projects technologies. The ecological-economic values of BPF and BPC system are \$28,300/yr and \$8,100/yr, respectively. Because both of the materials are renewable natural resources, the two biogas projects have high ecological-economic values and significant ecological environmental benefits. Most biogas from the project can meet the energy needs; biogas manure can be used as organic manure for crops, vegetables, and fruits. So they all improve the ecological-economy value.

3.3. Emergy Evaluation Index Analysis. All the emergy evaluation indices are classified by ecological-economic benefit, environmental benefit, and sustainable development ability (shown in Table 4).

3.3.1. Ecological-Economic Benefit. PER, natural emergy/purchase emergy, EIR, and ESR of BPF system are 0.32, 4.49, 0.22, and 1.42 times more than BPC system, respectively. This indicates that the BPF system depends less on renewable resources and has greater competitiveness and higher natural resources utilization efficiency and self-sufficiency ability than BPC systems. This is because BPC's material, corn straw, needs to be purchased, but BPF's material, feces, does not need fund support.

As to the net contribution of economic, although the feedback emergy of the two systems appears to be the same, the EYR of BPF system is about 1.57 times more than that of BPC systems, because the BPF system has much more yield emergy, which means that the BPF system has low cost, good production efficiency, high emergy utilization efficiency, and competitiveness.

Considering all the previous indices, BPF system has higher ecological-economic benefit than BPC system.

3.3.2. Environmental Benefit. The %W of BPF system is about 1.43 times more than that of BPC systems. Raw materials of BPF system are livestock manure, poultry and urine. And the total fermentation volume is $624\,m^3$, which consists of a primary fermentation reactor ($400\,m^3$) and a secondary fermentation reactor ($224\,m^3$). On the other hand, the raw material of BPC system is only straw, with fermentation volume of $480\,m^3$. The wastes treatment quantities of the BPF system and BPC system converted into solar energy value are 5.67×10^{17} sej/yr and 1.27×10^{17} sej/yr, which means that BPF system, has higher degradation efficiency.

ELR is an important index which reflects the degree of influence of the system on the environment. The ELRs of BPF and BPC system are 0.13 and 0.53, which are both less than 1. The results show that the two systems have a small impact on environment. However, owing to the higher renewable emergy ratio and more wastes treatment quantity, BPF system has much higher environmental benefit.

3.3.3. The Analysis of Sustainable Development Ability. To analyze sustainable development ability, there are three parts to be considered: FYR, %R, and ESI.

The first index is FYR. FYR is the ratio of the emergi of system self-feedback (for a biogas system, it is the part of biogas heated) divided by economy feedback emergy. The economic feedback emergies of BPF and BPC are 7.81×10^{16} sej/yr and 7.92×10^{16} sej/yr, while the self-feedback emergies are 3.97×10^{17} sej/yr and 2.05×10^{17} sej/yr. The previous results are the result of the quantity of energy used to heat $400\,m^3$ primary fermentation reactor and $224\,m^3$ secondary fermentation reactors. The FYR of BPF is 1.96 times more than BPC, which means that the ability of BPF's self-organizing is much better than BPC's.

Another index is %R, which indicates the renewable character of the biogas system. The renewable energy and the emergy devoted to BPF are both more than the BPC system. At the same time, %R of BPF is 1.36 times more than the BPC system. The results show that the ability of the system renewable character of BPF is better.

The last index, ESI, states the relation between the environment and the emergy produced. A perfected biogas system has not only high output, but also a far-reaching influence. The ESI of BPF is 6.61 times more than the BPC system, which shows that the BPF system has bright sustainable development possibilities.

4. Conclusion

The large- and medium-sized biogas projects where materials are corn straw and feces both have high ecological-economic benefit. In this research, the ecological-economic values of BPF system and BPC system are \$28,300/yr and \$8,100/yr, respectively. According to the monetary, environment, and human production factors, both of the two types of biogas projects own great development potential.

As to the whole input emergy, renewable natural resources take the largest percentage, which means that both of the two systems have good treatment ability of agricultural waste (feces and crop straw). In the BPC system, the amount of biogas output is much more than biogas residues. With the rapid development of biogas projects, recycling treatment of waste and sewage has become a hot topic, and the comprehensive utilization of biogas residues has become a primary goal. Therefore, technology needs to be improved in order to utilize biogas residues efficiently.

Table 4: The comparative table of energy index.

Item	Evaluation index	BPC	BPF
Ecological-economy benefit	Purchased emergy ratio (PER)	0.38	0.12
	Natural emergy/purchased emergy	1.62	7.26
	Emergy investment rate (EIR)	0.62	0.14
	Emergy yield ratio (EYR)	8.86	13.95
	Emergy self-sufficiency ratio (ESR)	0.62	0.88
Environmental benefit	Waste processing ratio (%W)	61.30	87.89
	Environmental load ratio (ELR)	0.53	0.13
Sustainable development	Feedback yield ratio (FYR)	2.59	5.08
	Renewable ratio (%R)	65.15	88.70
	Sustainability index (ESI)	16.57	109.50

From the analysis of the point of emergy, BPF system is superior to BPC system in the aspects of ecological economic benefit, environmental benefit and the sustainable development ability. This result is due to problems of the difficulty of corn straw seasonal collection and degradation. As to this situation, BPC system can be considered if anaerobic digestion is combined with other raw materials, such as poultry and livestock manure, urine and household garbage.

Appendices

A.

Notes to Table 1:

(1) Underground water

Number: 2500 kg/d
Standard energy value: 4 kJ/ kg
Energy: 2500 kg/d $\times$ 4 $\times$ 10^3 J/kg $\times$ 365 d/yr = 3.65 $\times$ 10^9 J/yr

(2) Corn straw

Number: 900 kg/d
Standard energy value: 14355.72 kJ/kg
Energy: 900 kg/d $\times$ 14355.72 $\times$ 10^3 J/kg $\times$ 365 d/yr = 4.72 $\times$ 10^{12} J/yr

(3) Human labor

Days: 4 $\times$ 365 d/yr = 1460 d/yr
Standard energy value: 12600 kJ/d
Energy: 1460 d/yr $\times$ 12600 kJ/d = 1.84 $\times$ 10^{10} J/yr

(4) Steel plate

Number: 3.5 $\times$ 10^7 g/20 yr = 1.75 $\times$ 10^6 g/yr

(5) Equipments, PE pipes

Number: (900000/20 yr) RMB/8.27 = 5.44 $\times$ 10^3 (2000 US$)

(6) Civil work cost

Number: (100000/20 yr) RMB/8.27 = 6.05 $\times$ 10^2 (2000 US$)

(7) Maintenance cost

Number: 5000 RMB/8.27 = 6.05 $\times$ 10^2 (2000 US$)

(8) Coal

Number: 18000 kg/yr
Standard energy value: 26777.6 kJ/kg
Energy: 18000 kg/yr $\times$ 26777.6 kJ/kg = 4.82 $\times$ 10^{11} J/yr

(9) Electricity

Number: 30000 kw·h/yr
Standard energy value: 3598.24 kJ/kw·h
Energy: 30000 kw·h/yr $\times$ 3598.24 kJ/kw·h = 1.08 $\times$ 10^{11} J/yr

(10) Protein powder

Number: (182.5 kg/yr $\times$ 4.2 RMB/kg)/8.27= 9.27 $\times$ 10^1 (2000 US$)

(11) Biogas (heated)

Number: 39600 m^3/yr
Standard energy value: 20920 KJ/m^3
Energy: 39600 m^3/yr $\times$ 20920 KJ/m^3 = 8.28 $\times$ 10^{11} J/yr
Number: 76500 m^3/yr
Standard energy value: 20920 kJ/m^3
Energy: 76500 m^3/yr $\times$ 20920 kJ/m^3 = 1.60 $\times$ 10^{12} J/yr

(12) Biogas (output)

Number: 133200 m^3/yr
Standard energy value: 20920 kJ/m^3

Energy: 133200 m^3/yr × 20920 kJ/m^3 = 2.79 × 10^{12} J/yr

Number: 157500 m^3/yr

Standard energy value: 20920 kJ/m^3

Energy: 157500 m^3/yr × 20920 kJ/m^3 = 3.29 × 10^{12} J/yr

(13) Nitrogen fertilizer

Number: 6.58 × 10^5 g/yr

(14) Phosphate fertilizer

Number: 3.29 × 10^5 g/yr

(15) Potash fertilizer

Number: 4.94 × 10^5 g/yr

B.

Notes to Table 2:

(1) Solar energy

Standard energy value: 4.1868 × 10^3 J/kg·k

Energy: 50 m^3/d × 10^3 Kg/m^3 × 120 d/yr × 4.1868 × 10^3 J/(Kg·k) × 5 k = 1.26 × 10^{11} J/yr

(2) Solid manure

Number: 4.015 × 10^6 kg/yr

Total solid: 18%

Standard energy value: 13500 kJ/kg

Energy: 4.015 × 10^6 kg/yr × 18%× 13500 kJ/kg = 9.76 × 10^{12} J/yr

(3) Urine (including flushing sewage)

Number: 12410 m^3/yr

Standard energy value: 6.43 × 10^6 J/m^3

Energy: 12410 m^3/yr × 6.43 × 10^6 J/m^3 = 7.98 × 10^{10} J/yr

(4) Human labor

Days: 3 × 365 d/yr = 1095 d/yr

Standard energy value: 12600 kJ/d

Energy: 1095 d/yr × 12600 kJ/kg = 1.38 × 10^{10} J/yr

(5) Civil work cost

Number: (734000/30 yr)RMB/8.27= 2.96 × 10^3 (2000 US$)

(6) Equipments, PE pipes

Number: (1289000/30 yr)RMB/8.27 = 5.20 × 10^3 (2000 US$)

(7) Appurtenant work

Number: (176000/30 yr)RMB/8.27 = 7.10 × 10^2 (2000 US$)

(8) Maintenance cost

Number: 5000 RMB/8.27 = 6.05 × 10^2 (2000 US$)

(9) Coal

Number: 13600 kg/yr

Standard energy value: 26777.6 k J/kg

Energy: 13600 kg/yr × 26777.6 kJ/Kg = 3.64 × 10^{11} J/yr

(10) Electricity

Number: 20221 kw·h

Standard energy value: 3598.24 kJ/kw·h/yr

Energy: 20221 KW·h/yr × 3598.24 kJ/kw·h = 7.28 × 10^{10} J/yr

(11) Biogas (heated)

Number: 76500 m^3/yr

Standard energy value: 20920 kJ/m^3

Energy: 76500 m^3/yr × 20920 kJ/m^3 = 1.60 × 10^{12} J/yr

(12) Biogas (output)

Number: 157500 m^3/yr

Standard energy value: 20920 kJ/m^3

Energy: 157500 m^3/yr × 20920 kJ/m^3 = 3.29 × 10^{12} J/yr

(13) Nitrogen fertilizer

Number: 8.63 × 10^3 kg/yr

(14) Phosphate fertilizer

Number: 1.02 × 10^4 kg/yr

(15) Potash fertilizer

Number: 1.73 × 10^4 kg/yr.

Acknowledgment

The research work is supported by the National Key Technology R&D Program of China (nos. 2008BADC4B03 and 2009BAC64B08).

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Hindawi Publishing Corporation
The Scientific World Journal
Volume 2013, Article ID 717054, 7 pages
http://dx.doi.org/10.1155/2013/717054

Research Article

Greenhouse Gas Inventory of a Typical High-End Industrial Park in China

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Received 11 December 2012; Accepted 9 January 2013

Academic Editors: N. H. Afgan, A. Bahadori, M. Gambino, and A. L. Mayer

Global climate change caused by greenhouse gas (GHG) emissions, which severely limits the development of human society and threatens the survival of humanity, has drawn the international community's long-term attention. Gathering the most important production factors in the region, an industrial park usually represents the development level of specific industries in the region. Therefore, the industrial park should be regarded as the base unit for developing a low-carbon economy and reducing GHG emissions. Focusing on a typical high-end industrial park in Beijing, we analyze the carbon sources within the system boundary and probe into the emission structure in view of life-cycle analysis. A GHG inventory is thereby set up to calculate all GHG emissions from the concerned park. Based on the results, suggestions are presented to guide the low-carbon development of the high-end industrial park.

1. Introduction

Global climate change caused by greenhouse gas (GHG) emissions, which severely limits the development of human society and threatens the survival of humanity, has drawn the international society's attention. China has been considered as the largest GHG emitter in the world, and the Chinese government has been taking various measures to reduce GHG emission and mitigate climate change [1–6]. Among them, China is committed to cut the CO_2 emission per unit of GDP by 40–45% by 2020 against the 2005 level [7]. Within this context, low-carbon economy provides an efficient development path that maximizes the value in a low consumption, low pollution, and low GHG emission mode [8, 9].

Industrial parks are characterized as a clustering of industries designed to meet compatible demands of different organizations within one location [10]. Industrial agglomeration has proven to be vital to the economic growth of developed countries, as well as less-developed ones like China [11, 12]. According to the data from the Ministry of Land and Resources in China 2011, there were 208 nationally designated industrial parks and more than 3000 provincial ones in China. For the industrial land, the average fixed investment was 48.1 million RMB per hectare, and the output was 125.6 million RMB per hectare [13–15]. Taking Beijing as an example, all the industrial parks' contribution to the urban economy accounted for 24%. Collecting most important factors of production in the region, an industrial park usually represents the development level of specific industries in the region. Therefore, the industrial park should be regarded as the base unit for developing industrial economy and also a breakthrough for regional resource allocation and environmental management. With the emergence of low-carbon economy, more and more industrial parks are seeking a low-carbon mode incorporating production, consumption, and resource allocation issues.

In the industrial park, enterprises of identical or similar industries are not simply spatially concentrated. The administrator must plan the layout, build the public infrastructure, and handle the daily maintenance. Therefore, GHG emissions from industrial parks could be divided into two parts, and the responsibility for emission cutting could be shared by different parties including the enterprises and the administrator of the park. Currently, there have been increasing research interests focused on the GHG emissions from enterprises and industrial sectors, shaping the GHG inventories in expanding scopes, from the combustion of fossil fuel to the whole production chain [16–21]. This means, in spite of the direct emission from energy consumption and chemical process, the inventories also include indirect emission owing to the total supply chain extend to the production gate [22]. In fact, it is necessary to calculate the GHG emission from the perspective of administrators and put forward useful suggestions on carbon reduction, which may supplement the existing literatures and help industrial parks achieve the low-carbon mode.

High-end industrial park is a type of industrial park that usually agglomerates the head offices or research and development centers of high-tech industries. There are few manufacturing productive processes in such industrial parks, so less fossil fuel and fewer raw materials are consumed by the enterprises. As a result, the administrator would take more responsibilities compared to those of the other types of industrial parks. In this paper, a GHG inventory is set up to analyze the life-cycle GHG emissions of a high-end industrial park in Beijing. Based on the results, suggestions are given to guide the low-carbon development of the high-end industrial park.

2. Methodology

The life cycle of a high-end industrial park is divided into three stages, that is, construction stage, operation stage, and demolition stage. In the construction stage, the concerned buildings and affiliated municipal facilities are constructed, as well as the garden landscape. The operation stage usually lasts for 40 to 50 years. During this stage, the industrial parks need to consume a large amount of electricity, heat power, and water. Meanwhile, wastewater and solid waste are discharged daily from the buildings and public space. As a general rule, a high-end industrial park has a 50-year term for the land use rights, and then it goes into the demolition stage. In this study, the GHG emission in the demolition stage is estimated based on the size and construction structure of the industrial park.

We consider three types of GHGs, that is, carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O). The inventory includes five sorts of GHG emissions sources: (1) direct and indirect emission from the consumption of primary energy and second energy; (2) direct emission from industrial production process; (3)-(4) emission from the production and transportation processes of all the materials and equipment used in the high-end industrial park; (5) emission from the sewage treatment and solid waste disposal processes.

2.1. Energy Consumption. Energy consumption is an important source of GHG emissions in the industrial park. As defined in this study, energy consumption processes involved mainly includes fossil fuel combustion, electricity and heat energy production, and transportation vehicles. The estimation of the GHG emission from above processes refers to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [22].

For the fossil fuel combustion, (1) is given as

$$E^{c}_{\mathrm{GHG},i} = Q^{c}_{i} \times \mathrm{EF}^{c}_{\mathrm{GHG},i}, \tag{1}$$

where $E^{c}_{(\mathrm{GHG},i)}$ is the emissions of a given GHG by type of fuel (kg), Q^{c}_{i} is the amount of fuel combusted (TJ), and $\mathrm{EF}^{c}_{\mathrm{GHG},i}$ is the emission factor of a given GHG by type of fuel (kg GHG/TJ).

For the electricity and heat energy production processes, if the power comes from the sectors outside the industrial park, the concerned GHG emission can be calculated according to the average energy consumption level of the local sector. If the power is produced by the enterprise just in the industrial park, the concerned GHG emission can be estimated as zero to avoid the repeated calculation based on the fossil fuel of combustion process. Equation (2) is presented to calculate the GHG emission from electricity and heat energy production processes as

$$E^{e}_{\mathrm{GHG}} = Q^{e} \times \mathrm{EF}^{e}_{\mathrm{GHG}}, \tag{2}$$

where E^{e}_{GHG} is the emissions of a given GHG by electricity or heat (kg), Q^{e} is the amount of electricity or heat produced (kWh or TJ), and $\mathrm{EF}^{e}_{\mathrm{GHG}}$ is the emission factor of a given GHG by electricity or heat (kg GHG/kwh or kg GHG/TJ).

As for the transportation process, it refers to the transportation of the energy resources, raw materials, instruments and equipment from the origin to the industrial park. The GHG emissions from the transportation process can be estimated from the fuel consumed:

$$E^{t}_{\mathrm{CO}_2} = \sum_{i} \left(Q^{t}_{i} \times \mathrm{EF}^{t}_{\mathrm{CO}_2,i} \right), \tag{3}$$

where $E^{t}_{\mathrm{CO}_2}$ is the emissions of CO_2 (kg), Q^{t}_{i} the fuel consumed (TJ), and $\mathrm{EF}^{t}_{\mathrm{CO}_2,i}$ is the emission factors (kg CO_2/TJ), or calculated by the distance covered by the vehicles as

$$E^{t}_{\mathrm{NH}_4,\mathrm{N}_2\mathrm{O}} = \sum_{a,b,c,d} \left(L_{a,b,c,d} \times \mathrm{EF}^{t}_{a,b,c,d} \right) + \sum_{a,b,c,d} C_{a,b,c,d}, \tag{4}$$

where $E^{t}_{\mathrm{NH}_4,\mathrm{N}_2\mathrm{O}}$ is the emissions of CH_4 or N_2O (kg), $L_{a,b,c,d}$ is the distance travelled during thermally stabilized engine operation phase for a given mobile source activity (km), $\mathrm{EF}^{t}_{a,b,c,d}$ is the emission factor (kg/km), $C_{a,b,c,d}$ is the emissions during warm-up phase (cold start)(kg), a is the fuel type (e.g., diesel, gasoline, natural gas, and LPG), b is the vehicle type, c is the emission control technology (such as uncontrolled, catalytic converter, etc.), and d is the operating conditions (e.g., urban or rural road type, climate, or other environmental factors).

In general, the first approach (fuel sold) is appropriate for CO_2 while the second (distance travelled by vehicle type and road type) is suitable for CH_4 and N_2O.

2.2. Industrial Production. The GHG emissions from industrial production processes of specific products are mainly due to the physical or chemical reaction rather than the combustion of fossil fuels. In an industrial park, the GHG type and amount depend on the leading industry type, and the accounting method varies accordingly. According to the activity data obtained and the applicable scope of emission factors, there are two scales to calculate the emission from the industrial production process: an industry or a product. If it is an industry, the calculation is less precise. The activity data can be the economic scale (such as the GDP) or the production scale (such as the production output), and the emission factors can be the recommended ones by IPCC or the average level of the specific countries or territories. Regarding a product, the calculation must focus on the supply chain of the product, even narrowed down to production device and working conditions. For a high-end industrial park in this study, there is almost no real supply chain of product.

2.3. Material Input. Similar to the electricity and heat energy production processes, repeated calculations should also be avoided when studying the GHG emission due to the material input. There is a development trend of the industrial parks that more and more industrial parks will generate internal logistics networks, and then the products, by-products, or waste of one enterprise will soon be used by another enterprise as raw material or energy. Therefore, in this study, the objects are the materials coming from the outside, and the calculation will cover all the GHG emission during the production and transportation processes that is usually defined as "from cradle to gate." GHG emission of this part could be calculated by

$$E^{m}_{\mathrm{GHG},i} = Q^{m}_{i} \times \mathrm{EF}^{m}_{\mathrm{GHG},i}, \quad (5)$$

where $E^{m}_{\mathrm{GHG},i}$ is the emissions of GHG during the production and transportation processes of type of material (kg), Q^{m}_{i} is the amount of material input, and $\mathrm{EF}^{m}_{\mathrm{GHG},i}$ is the emission factor.

2.4. Equipment Employment. Some equipment will be applied directly by enterprises for industrial production activities, such as blast furnace and converter that are essential to iron and steel industry; and the other equipment will be used to maintain the daily operation of the industrial parks such as water pump, draft apparatus, and so forth. Similar to the material input process, the calculation of equipment employment will also cover the "from cradle to gate" GHG emission. There are two methods to obtain the emission factors of equipment: (1) one is based on the input-output between the equipment production sector and other sectors, and the result will be in the form of GHG emission per unit currency, as described in [23, 24]; (2) the other one is to analyze the raw materials dosage and processing energy consumption of a specific equipment, and the result will be in the form of GHG emission per piece of equipment, as described in references [25–27].

2.5. Sewage Treatment and Solid Waste Disposal. The conventional disposal of solid waste is landfill, composting, and burning. The landfill and composting will mainly generate CH_4, and burning produces CO_2. Currently, landfill is the most popular method in the Chinese cities to dispose of the solid waste, and the technology of GHG collection under such condition is developing rapidly and being promoted widely. In this study, the GHG emission from solid waste disposal process will be calculated using the first-order attenuation method as recommended by IPCC as

$$E^{s}_{\mathrm{CH}_4} = \left(\sum_{x} E^{s}_{\mathrm{CH}_4,x,T} - R_T\right) \times \left(1 - \mathrm{OX}_T\right), \quad (6)$$

where $E^{s}_{\mathrm{CH}_4}$ is the emission of CH_4 from solid waste disposal (kg), $E^{s}_{\mathrm{CH}_4,x,T}$ is the emission of CH_4 from a type of solid waste disposal (kg), R_T is the recovery of CH_4 (kg), and OX_T is the oxidation factor (%).

The usual sewage anaerobic treatment will discharge CH_4 and N_2O, where the amount depends on the contents of biodegradable organics and nitrogenous substance in the sewage water. The calculation method recommended by IPCC is chosen to estimate the GHG emission from the sewage treatment process as

$$E^{w}_{\mathrm{CH}_4} = \mathrm{TOW} \times \mathrm{EF}^{w}_{\mathrm{CH}_4} - R, \quad (7)$$

where $E^{w}_{\mathrm{CH}_4}$ is the emission of CH_4 from sewage treatment (kg), TOW the total organic degradable material in wastewater (kg), $\mathrm{EF}^{w}_{\mathrm{CH}_4}$ the emission factor (kg/kg), R is the recovered CH_4 (kg) and

$$E^{w}_{\mathrm{N}_2\mathrm{O}} = \mathrm{N}^{w} \times \mathrm{EF}^{w}_{\mathrm{N}_2\mathrm{O}} \times \frac{44}{28}, \quad (8)$$

where $E^{w}_{\mathrm{N}_2\mathrm{O}}$ is the emission of N_2O from sewage treatment (kg), N^{w} is the nitrogen in effluent (kg), $\mathrm{EF}^{w}_{\mathrm{N}_2\mathrm{O}}$ is the emission factor (kg/kg), and44/28 is the conversion factor of kg N_2O-N into kg N_2O.

3. Case Study

3.1. Data Sources. The concerned industrial park is located in the southwest of Beijing. It is a typical high-end industrial park known for its good environmental quality and high-end industry concentration. The park has an area of 119235.6 m^2. The building density is 31.62%, while the landscaping ratio is 41%, which means 1 square meter of park area is covered by 0.3162 square meters of building and 0.41 square meters of landscape. All the data in our case industrial park are obtained by field research, while the emission factors from the public data sources. In order to compare the results, all the GHG emissions in this study are converted to the form of CO_2-eq based on the global warming potential (GWP) recommended by IPCC [28].

3.1.1. Energy Consumption. The emission factors of primary energy are specific for China, which are referenced to the default emission factors by IPCC and the average lower heat values in China's energy statistics yearbook [29]. The emission factors of the secondary energy (such as the electricity and heat) are obtained based on the amount of primary energy consumed by the electricity and heat production sector in Beijing. The basic data can be found in the reports of the National Development and Reform Commission and *Beijing Statistical Yearbook* [30].

3.1.2. Industrial Production. The industrial park is designed with high-end positioning that is a well-operated cluster of the head offices or research and development centers of high-tech industries. Thus, the GHG emission of industrial production process in our case is neglected.

3.1.3. Material Input. As discussed in Section 3.1.2, there are few industrial production processes in such high-end industrial parks. We thus have the hypothesis that the raw material input necessary for industrial production can be ignored. As a result, this study focuses on the GHG emission from the construction materials input during the construction stage. The emission factors of the construction materials can be divided into 3 types [31–43].

Type 1. The products are easy to decide their boundaries and technological processes to choose the precise matching emission factors.

Type 2. The products are not well studied by life-cycle analysis but the production technological processes are clear. We can obtain the emission factors based on the amount of energy consumption and raw material input, on the condition that these energy consumption and raw material input are of Type 1.

Type 3. The products have never been studied. We have to select an alternative that has similar production process, raw material, and function, with an assumption that the emission factors of them are the same.

3.1.4. Equipment Employment. The method with which we obtained the emission factors of the equipment is the same with the material input. However, the equipment has a more complicated production process and various specifications and types, so it is difficult to make clear the exact emission factors of each piece of equipment [44–47]. As a result, the majority of equipment belongs to Type 3, and the uncertainty of the calculation results is increased.

3.1.5. Sewage Treatment and Solid Waste Disposal. According to the investigation, all the sewage generated by the case industrial park is discharged into the municipal drainage sewage pipe network, so we assume that the emission factors of the sewage from the industrial park are the same as the average of the municipal sewage in Beijing. With reference to the literatures [48, 49], the emission factors of the sewage treatment process are ($5.61E-03$) kg CO_2/kg, ($8.89E-08$) kg N_2O/kg, and ($1.59E-02$) kg CH_4/kg.

Similarly, the emission factors of the solid waste disposal process are assumed to be the same as the average level in Beijing. With reference to the literatures [50], the CH_4 correction factor (MCF) is 1.0, the dissolved organic carbon (DOC) 6.5%, the fraction of DOC dissolved (DOC_f) 0.5, the CH_4 volume fraction of the landfill gas 0.5, and the oxidation factor (OX_T) 0.1.

3.2. Results and Discussion. The GHG emission of each stage in the life cycle of the industrial park is calculated based on the proposed method. The overall GHG emission of the life-cycle is 1872177 t CO_2-eq. The construction stage takes up 4.546%, which amounts to 85105.82 t CO_2-eq GHG emission with an intensity of 801.69 kg CO_2-eq/m^2; the demolition stage takes up 0.102%, contributing 1917.3 t CO_2-eq GHG emission with an intensity of 18.06 kg CO_2-eq/m^2. As can be seen, the operation stage contributes the majority of GHG emission, which achieves a proportion of 95.352%. The GHG emission amount of operation stage is 37717.18 t CO_2-eq, with the intensity being 355.29 kg CO_2-eq/m^2.

The construction stage of the industrial park is decomposed into 12 steps with different functions, which are structure (S), indoor decoration (ID), outdoor decoration (OD), building electric (BE), building water supply and drainage (BWSD), heating (H), ventilation (V), fire protection (FP), road (R), municipal electric (ME), municipal water supply and drainage (MWSD), and landscaping (L). During the construction stage, GHG emission from construction material input process is accounted to be 82509 t CO_2-eq, which takes the 96.95% part of the stage. The contribution of each step to the amount can be found in Figure 1. As it is shown, the top three emission sources are S (59.71%), ID (20.33%), and OD (11.40%) and then L (3.74%), V (1.78%), and R (1.09%). The other six steps only take up the proportion of less than 1%.

The operation stage should be of the focus of GHG emission reduction in the industrial park for its significant contribution. In order to get more specific and meaningful results, the overall GHG emission of this stage is further decomposed into seven processes. As shown in Figure 2, the processes of sewage treatment, heat energy consumption and electricity consumption should be paid more attention, which contributes to 98.69% of the operation stage emission.

For the operation stage, some strategies are adopted to change the energy consumption and sewage treatment as shown in Table 1. The GHG emission of operation stage will decline as shown in Figure 3. The overall emission of operation stage will be reduced to 27443.58 t in 2020 and 17711.66 t in 2050, which are just 72.76% and 46.96% of those in 2011.

4. Conclusions

For a high-end industrial park, the GHG emission of the construction stage is very intensive with significant environmental impacts, which is a key point to be reckoned with by the administrators. Based on the calculation results, we

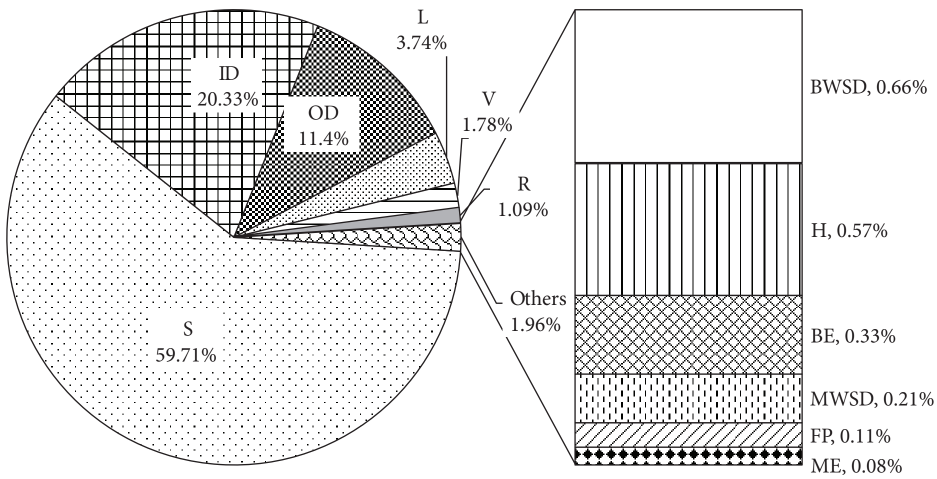

Figure 1: GHG emission from construction material of construction stage.

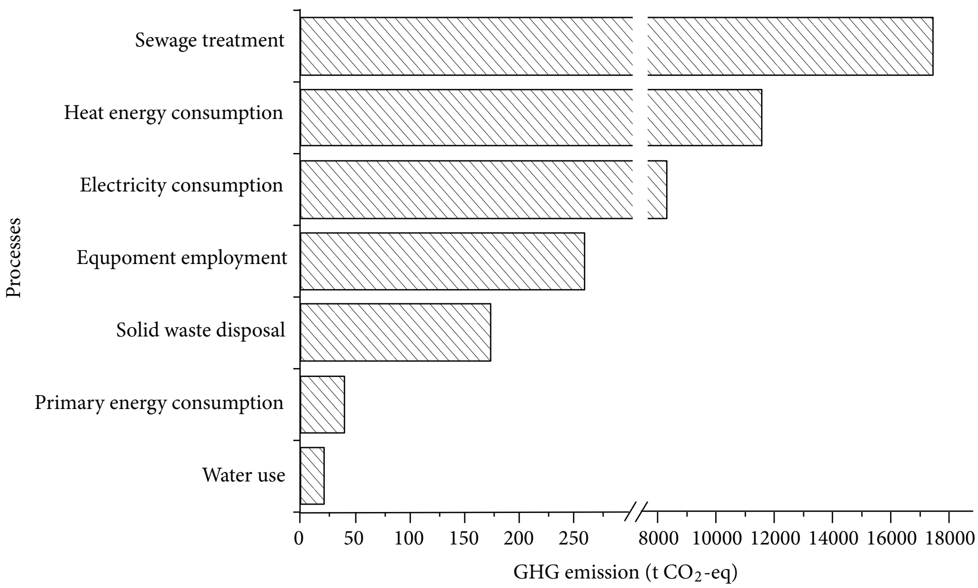

Figure 2: GHG emission of operation stage.

can control the GHG emission of construction stage in the following ways.

(a) *Using local construction materials to reduce the GHG emission from the transportation processes of the construction materials*. Most construction materials are of a large size and usually in high demand. Thus, there will be a considerable quantity variance of GHG emission between different transport distances. Employing the local construction materials can not only save the transportation cost and transportation time, but also reduce the GHG emissions, which may achieve much more benefits in economy and environment.

(b) *Employing the low-carbon and regeneration construction materials instead of the traditional ones to reduce the GHG emission from the upstream production process and downstream disposal*. After the quantitative evaluation of performance and cost, decision makers may prefer the low-carbon and regeneration construction materials. The low carbon and regeneration characteristics imply that these materials consume less energy and fewer resources during the production processes compared to the traditional materials, thereby having a better performance and lower price.

(c) *Optimizing the construction progress to promote a safe and low-carbon form of construction engineering*. The arrangement of the construction schedule can be optimized to ensure the project to be finished on time. For example, less night work can

Table 1: Scenario analysis of operation stages.

Emission source	Parameter	2010	2020	2030	2040	2050
Electricity consumption	Emission factor ($g\ CO_2$-eq/kWh)	996.36	862.52	759.91	654.78	552.17
Heat energy consumption	Emission factor ($kg\ CO_2$-eq/GJ)	101.43	44.88	39.27	33.66	28.05
Sewage treatment	Emission factor ($g\ CO_2$-eq/kg sewage)	435.45	413.20	392.21	372.22	353.21

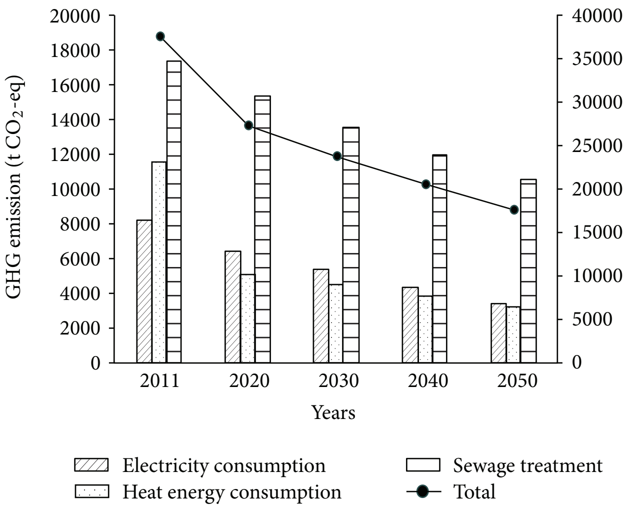

Figure 3: GHG emission of operation scenarios of different strategies.

avoid unnecessary power consumption and noise pollution.

The administrators of industrial parks should take the responsibilities to reduce the GHG emission during the operation stage, which normally lasts for about 40 to 50 years. As implied by the accounting result, more attention should be paid to the processes of sewage treatment, heat energy consumption, and electricity consumption when controlling the GHG emission of this stage. For example, the industrial park in our case produces 40,000 t sewages every year, and the treatment process of the sewage will result in a GHG emission of 17373.46 t CO_2-eq. Therefore, the administrator can control the emission by bringing in water saving technology and building the recovery system of waste water.

Acknowledgments

This study was supported by the Fund for Creative Research Groups of the National Natural Science Foundation of China (no. 51121003), Key Program of National Natural Science Foundation (nos. 50939001, 41271543), National Key Technology Research and Development Program (no. 2012BAK30B03), and Program for New Century Excellent Talents in University (NCET-09-0226). The authors are especially grateful for the financial support from Beijing Development Area Co., Ltd.

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The Scientific World Journal
Volume 2012, Article ID 625828, 8 pages
doi:10.1100/2012/625828

The ScientificWorldJOURNAL

Research Article

Material Flow Analysis of Fossil Fuels in China during 2000–2010

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Received 8 November 2012; Accepted 4 December 2012

Academic Editors: N. H. Afgan, H. Aras, and K. J. Chua

Since the relationship between the supply and demand of fossil fuels is on edge in the long run, the contradiction between the economic growth and limited resources will hinder the sustainable development of the Chinese society. This paper aims to analyze the input of fossil fuels in China during 2000–2010 via the material flow analysis (MFA) that takes hidden flows into account. With coal, oil, and natural gas quantified by MFA, three indexes, consumption and supply ratio (C/S ratio), resource consumption intensity (RCI), and fossil fuels productivity (FFP), are proposed to reflect the interactions between population, GDP, and fossil fuels. The results indicated that in the past 11 years, China's requirement for fossil fuels has been increasing continuously because of the growing mine productivity in domestic areas, which also leads to a single energy consumption structure as well as excessive dependence on the domestic exploitation. It is advisable to control the fossil fuels consumption by energy recycling and new energy facilities' popularization in order to lead a sustainable access to nonrenewable resources and decrease the soaring carbon emissions.

1. Introduction

Material flow analysis (MFA), quantified by material weight instead of currency, is built on the theories of industrial metabolism and social metabolism to pursue the translation path from nature to human ecosystem as well as the final regressive sinks [1]. The basic standpoint of MFA is that environmental effects which are brought about via social economic behaviors are mainly dependent on the quantity and quality of natural resources and materials devoted in the ecosystem, and the wastes translated from the consumption sectors back to the environment.

MFA is viewed as a significant measure to study the metabolism of material and resources. Ayres and Kneese firstly presented the first material flow accounts on the national level in 1969 [2]. During 1970s–1980s, the perfection of material balance and industrial metabolism theories laid a solid foundation for MFA application in the whole ecosystem. Austria, Japan, and Germany took the lead in calculating substance and natural resources in domestic economic scope in 1990s [3]. Subsequently, developed countries such as The Netherlands, America, and Australia finished their MFA in national boundary [1, 4]. In 2001, EU Statistics Department published a handbook about MFA research technique applied to ecosystem for the first time in the world [5], which enormously accelerated the promotion of MFA in economic field. Muñoz and Hubacek pointed out in 2008 that the economic growth was the major source of material changes [6] Chen proposed in his study in 2007 that the driving force of the social-economic-ecological complex system was the resource, which posed unparalleled challenges on each level of the society. The quantity and quality scarcities of the diverse resources require an efficient, effective, and interdependent utilization based on overall and unified accounting [7]. In recent years, China has also done necessary studies in MFA and gained achievements in scientific research of the relationship between total material input and consumption in the national base [8–10].

In the early 1990s, The concept of "ecological rucksacks" was firstly proposed which was commonly accepted as "hidden flows" afterward [11]. This concept refers to the wastes inevitably produced in the process of resource exploitation, though it is not devoted to the social production. Without creating commercial value, it will exert a huge influence on natural and social environment. In view of this, MFA is further modified and becoming an effective tool in

Table 1: Population and GDP information of China during 2000–2010.

Year	Total population (million)	Gross domestic product (¥ billion)
2000	1267.43	9921.5
2001	1276.27	10965.5
2002	1284.53	12033.3
2003	1292.27	13582.3
2004	1299.88	15987.8
2005	1307.56	18308.5
2006	1314.48	21087.1
2007	1321.29	24953.0
2008	1328.02	31404.5
2009	1334.50	34090.2
2010	1340.91	40120.2

measuring the balance between the resource depletion and the social development [12].

In this study, MFA's method is applied to the Chinese fossil fuels as a research case with certain modifications of hidden flows, which is considered as the more exact mode in accounting resource consumption. The results can make acceptable recommendations not only in transferring materialized into dematerialized consumption pattern, but also in building a low-carbon economy and coping with global warming.

2. Methodology and Data

The study period, lasting from 2000 to 2010, was an important stage for China's rapid economic progress in history. The rapid growth in the fields of both economy and resource exploitation is producing far-reaching impacts in social and environmental areas for today's decision making and stratagem implement. The basic information of China during the study period is listed as background information in Table 1.

Currently, a systemic MFA framework based on the national or regional ecosystem has been initially established all over the world, which has been comprehensively applied in occidental countries. The input stream of fossil fuels was divided into two parts, direct input flows, and hidden flows. The study boundary was confined into the domestic ecosystem. The input fossil fuels which come from the domestic production and abroad import contain raw coal, oil, and natural gas, excluding secondary energy input. Moreover, Wuppertal evaluated the average ratio of global hidden flow (GHF), and the results showed that crude oil, natural gas, and raw coal were 1 : 1.22, 1 : 1.66 [13], and 1 : 2.36 [14], respectively in view of the fact that most coal in China belongs to bastard coal. Usually the output stream of fossil fuels refers to direct output and contaminated discharge. Due to different burning efficiencies and regional variation in technologies, it is inaccurate to calculate direct output at the end of MFA. To express the end-result of the fossil fuels in the whole process of material flow, this paper chose three indexes, consumption and supply ratio (C/S Ratio), resource consumption intensity (RCI), and fossil fuels productivity (FFP) by considering population, GDP, and total energy input, to evaluate the influences of resource consumption in the fields of society and economy as well as environment. The three indexes are defined as follows:

$$\frac{S}{C} = \frac{\text{Consumption}}{\text{Production} - \text{Export} + \text{Import}} \times 100\%,$$
$$\text{RCI} = \frac{\sum \text{Consumption} \times \text{GHF}}{\text{Population}}, \quad (1)$$
$$\text{FFP} = \frac{\text{GDP}}{\sum \text{Consumption} \times \text{GHF}},$$

in which, the units are tsc/person ("tsc" refers to ton of standard coal (we use tsc for short in the rest part of this paper); standard coal, also known as coal equivalent, unified calorific value standard, different varieties, different energy contents of different calorific values converted to the calorific value of 7,000 kcal per kg of standard coal) for RCI, \$/tsc for FFP (it is better for further comparison with other countries when we replace the currency unit from "¥" to "\$").

All the data sources are acquired from publications, such as Energy Statistical Yearbooks of different years [15] and China Statistical Yearbooks [16] and websites [17]. In order to seek unity of economic value and avoid inflation or deflation in different times, we defined the year of 2000 as a base year, in which year the price was chosen as constant price; therefore, pure monetary value in all the other years should be converted into a standard value of 2000. The original yield and import/outport flows of three primary fossil fuels are listed in Table 2.

According to IPCC 2006 [18], different types of fuels have their own carbon emission coefficients (we use CEC in the following part of this paper), for coal, oil, and natural gas, the transition factors are listed in Table 4. Therefore, the CO_2 emission distributions will be obtained on the basis of fossil energy structure.

3. Results and Discussion

C/S ratio is of a paramount importance for the national or regional sustainability. A high value (>1) of C/S ratio means more resources will be depleted, and then more wastes or disturbuances will occur along with environmental deteriorations and nonrenewable energy shortage. If the C/S ratio is low, on the one part, it is good news that the present fossil energy supply is sufficient for demand. On the other part, it provides an important implication to readjust the energy consumption and supply relationship in the national level. The index called RCI can reflect the personal access to fossil resource in China. FFP denotes the transfer ability from raw fossil material occupation into economic value, which usually represents the efficiency of the resource consumption. The accounting of MFA and different indexes from 2000 to 2010 is shown in the following table (RMB exchange rate against the US dollar to compare this quota after conversion with different countries in a unified

Table 2: The original yield and import/outport flows of three primary fossil fuels during 2000–2010.

Year	Coal			Oil			Natural gas		
	Yield (million tsc)	Export (million ton)	Import (million ton)	Yield (million tsc)	Export (million ton)	Import (million ton)	Yield (million tsc)	Export (billion cu.m)	Import (billion cu.m)
2000	988.55	55.06	2.17	232.28	10.30	70.26	36.46	3.1	0
2001	1050.28	90.12	2.66	234.51	7.55	60.26	40.28	3.0	0
2002	1107.32	83.89	11.25	238.03	7.66	69.40	43.69	3.2	0
2003	1309.92	94.02	11.09	242.38	8.13	69.40	46.41	1.8	0
2004	1516.15	86.66	18.61	2517.01	11.46	122.72	55.06	2.4	0
2005	1677.85	71.68	26.17	259.46	8.07	126.82	64.86	2.9	0
2006	1806.25	63.23	38.25	262.34	6.34	145.18	78.93	2.9	1.0
2007	1921.35	53.17	51.01	267.06	3.98	163.17	91.49	2.6	4.0
2008	2001.03	45.43	40.40	273.57	4.16	178.88	106.56	3.2	4.6
2009	2122.80	22.40	125.83	271.87	5.07	203.79	112.59	3.2	7.6
2010	2271.40	19.03	164.78	290.97	3.03	239.31	127.67	4.0	16.5

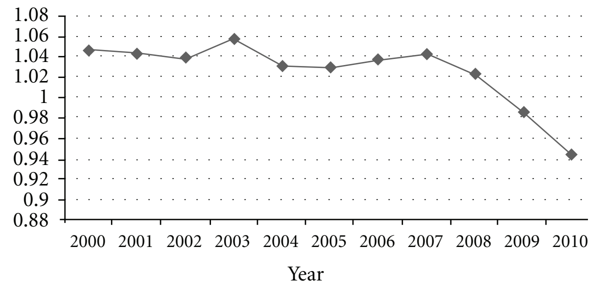

Figure 1: C/S ratio of fossil fuels in China during 2000–2010.

standard), and all the material flows are measured by the unit of "tsc," and the fossil fuels' consumption for three types of energy are collected in Tables 3(a) and 3(b).

3.1. Diversification of C/S Ratio See Figure 1. During the years from 2000 to 2007, it was nearly stable between 1 and 1.05 implying that a certain amount of previous fossil stock should be used to solve the supply and demand difference. During this period, there was a minor peak in 2003, reflecting that the obvious expansions of real estate construction, iron, and cement based heavy industry soaring development, which lead to the remarkable tension for energy supply and consumption relation. And after 2008, this ratio is fluctuate by most time lower than 1, which mainly attribute to the implementation of "energy saving and emission reduction" strategies in industries and domestic using. Generally speaking, from 2000 to 2010, C/S ratio of fossil fuels was decreasing roughly and the energy balance was trending into a capable supply state. Meanwhile, to better control the C/S ratio is an effective device to control the energy balance in the original production and final consumption.

Considering three kinds of fuels, coal yield was the main growth factor, which indicated that the energy structure in China was mainly based on raw coal as the dominant sector. Moreover, coal domestic production had occupied a share ranged 73–77% compared, and for oil was around 20% with total fossil energy during the past 11 years. The coal dominated energy structure has not dramatically reversed in that period. On average, the requirement of oil in occident countries account for 35% [11] of the total energy, that means we have a long way to amend the energy consumption structure, especially adding new energy into consideration, such as wind power, bioenergy, and tidal energy. Oil supply in China will not be sufficient forever, an urgent support policy is needed to encourage powerful companies and organizations to blend in the international arena and exploit a high quality resource. Furthermore, the domestic natural gas yield as well as the import proportion was enlarging, which indicated a good transition in enriching energy diversity and equitability, but with a too slight step. Therefore, we still have an adequate space to optimize the energy allocation so as to change the irrational existing state of fossil fuels consumption.

3.2. Diversification of RCI. RCI is an indicator that can express the level of per capita resource possess. Table 5 indicates that RCI was 2.1 times in 2010 than that in 2000, which implied that as individuals grow more affluent, their demands move beyond basic needs. The enormous requirements for private car, energy-consumption electronic products made life quality improve deeply on the one hand, and, on the other hand, extremely aggravated fossil resources depletion. The only solution to avoid energy crisis, especially

Table 3: (a) The fossil fuels' consumption from 2000 to 2010 in China (unit: million tsc). (b) The fossil fuels' supply[2] from 2000 to 2010 within China (unit: million tsc).

(a)

Year	Coal	Oil	Natural gas	Total consumption
2000	1007.07	323.08	32.02	1362.17
2001	1027.27	3278.89	36.10	1391.26
2002	1084.13	355.53	38.26	1477.93
2003	1282.87	389.64	45.95	1718.46
2004	1483.52	454.66	53.36	1991.54
2005	167.08	467.27	61.36	2199.49
2006	1839.19	499.24	75.02	2413.45
2007	1994.41	527.36	92.57	2614.33
2008	2048.88	533.35	107.84	2690.07
2009	2158.79	548.90	119.59	2827.29
2010	2209.59	617.38	142.97	2969.94

(b)

Year	Coal	Oil	Natural gas	Total
2000	950.77	317.94	32.65	1301.37
2001	987.81	309.82	36.60	1334.22
2002	1055.44	326.24	39.81	1421.48
2003	1250.69	329.92	44.14	1624.75
2004	1467.55	410.66	52.10	1930.30
2005	1645.35	429.11	61.26	2135.72
2006	1788.42	460.70	76.57	2325.68
2007	1919.81	494.48	93.22	2835.45
2008	1997.45	523.18	108.20	2628.83
2009	2196.68	555.76	117.96	2870.41
2010	2375.52	628.53	142.77	3146.82

[2] Supply = production − outport + inport.

Table 4: The carbon emission coefficients (CEC) for three types of fossil fuels.

Items	CEC
Coal	1.98 ton CO_2/ton
Oil	3.07 ton CO_2/ton
Natural gas	2.19 ton CO_2/ton

for nonrenewable energy, is to elevate utilization efficiency and attempt new renewable energy. In addition, China is the most populous developing country, whose contradiction between large energy-needed population and low per capita energy possession is always restricting the whole national development in social and economic fields. In addition, CEC from different types of the fossil fuel consumption from 2000 to 2010 in China is shown in Table 6 as a supplementary database.

3.3. Diversification of FFP. FFP, an economic value produced by the unit natural nonrenewable resource. Table 7 clearly illuminates that an obvious disparity is existing in fossil fuel productivity compared with the major energy-saving country. The level of fossil fuel productivity in China in 2010 was merely equivalent to that of The Netherlands in 1996, and Austria, Germany, and Great Britain had already owned this index nearly 1.5 times higher than that of China in 2010. The bog standard of FFP in China means not only a colossal waste of fossil fuels in production and consumption process, but also severe environmental pollution resulting in a great number of pollutants and wastes in all processes by using natural resources. The evident gap between China and other developed countries in creating economic value per unit fossil resource reflected low efficiency in energy input-output course. It is well accepted that economic development based on the extensive resource depletion is not the intrinsic pursuit of sustainable developing pattern, and it is needed to consummate a resource recovery system as soon as possible, promote the use of energy saving products in public, and participate in international cooperation that can develop bilateral and multilateral as well as regional collaboration in the field of new energy using and low-carbon technology [19]. Another step to solve the inefficiency in fossil fuel productivity is to change the approach of using fossil fuels into a closed material cycle mode [20] and enhance the GDP value created by per unit energy expending.

3.4. Comprehensive Analysis about Different Indexes. The variation trends of population, GDP, and RCI as well as FFP are illustrated in Figure 2. First, the population increased steadily which was fitting in with the national conditions during that time; second, GDP increased with an accelerating trend, which was not only due to the economic dynamic times in this period, but also affected by the appreciation of RMB since 2005; third, RCI was increased especially after the year 2002, meaning a society with the rapid consumption for fossil fuels; and finally, the variation of FFP was divided into two subperiods: the first half was nearly fair, however, the other half was soaring for a rapid fossil fuel economic productivity. Generally speaking, economy in China is operating well, but the extensive mode of growth could not change at once, with fossil fuel productivity impossibly boosted in a short time. However, infrastructures on fossil energy being or having been built will certainly carry weight in both economic development and the resource consumption.

3.5. CO_2 Emission Analysis. From Figure 3, it was clearly demonstrated the CO_2 emission distribution, and coal is the most carbon source. In China, the hidden flow ration for coal was the highest, and the energy structure could not be changed on the basis of coal consumption. That is why CEC from coal was nearly 2 times than that from oil and natural gas. From this result, using natural gas or the other low carbon emission energy is the most effective and urgent strategy for the government decision and public choice.

4. Conclusion

This paper analyzes the input of fossil fuels in China during 2000–2010 and proposed several indicators of MFA.

Table 5: C/S ratio, RCI, and FFP of China during 2000–2010.

Year	C/S ratio	Population million	RCI (tsc/person)	GDP (¥ billion)	Exchange rate (¥/100 $)	GDP ($ billion)	FFP ($/tsc)
2000	1.0467	1267.43	2.11	9921.4	827.84	1198.46	424.39
2001	1.0427	1276.27	2.22	10965.5	827.70	1324.82	459.32
2002	1.0397	1284.53	2.32	12033.2	827.70	1453.82	475.76
2003	1.0577	1292.27	2.68	13582.2	827.70	1640.97	458.47
2004	1.0317	1299.88	3.059	15987.8	827.68	1931.64	466.09
2005	1.0299	1307.56	3.35	18493.7	819.17	2257.62	489.17
2006	1.0377	1314.48	3.59	21631.4	797.18	2713.50	534.76
2007	1.0426	1321.29	3.79	26581.0	760.40	3495.67	635.13
2008	1.0233	1328.02	3.94	31404.5	694.51	4521.83	798.20
2009	0.9850	1334.50	4.14	34090.2	683.10	4990.53	836.92
2010	0.9438	1340.91	4.42	40120.2	696.95	5756.54	927.70

Table 6: CEC from different types of the fossil fuel consumption from 2000 to 2010 in China.

Year	Coal consumption (million ton)	Oil consumption (million ton)	Natural gas consumption (million ton)	CEC from coal (million ton CO_2)	CEC from Oil (million ton CO_2)	CEC from natural gas (million ton CO_2)
2000	1409.87	226.15	18.92	2791.55	694.28	41.45
2001	1438.15	229.51	21.34	2847.54	704.61	46.73
2002	1517.75	248.87	22.62	3005.15	764.02	49.54
2003	1795.97	272.74	27.16	3556.03	837.31	59.49
2004	2076.88	318.26	31.55	4112.23	977.04	69.09
2005	2339.15	327.09	36.27	4631.52	1004.15	79.44
2006	2574.80	349.46	44.35	5098.12	1072.85	97.13
2007	2792.12	369.14	54.72	5528.39	1133.26	119.85
2008	2868.37	373.33	63.75	5679.38	1146.14	139.62
2009	3022.25	384.22	70.70	5984.05	1179.55	154.84
2010	3093.35	432.16	84.53	6124.84	1326.73	185.12

In comparison with other countries, main conclusions are summed up as follows.

Generally speaking, the demand structure of coal, oil, and natural gas during the past 11 years has not changed significantly. The turning point of fossil fuel productivity appeared in 2002, and increased dramatically after 2005. Both phenomena are decided by international economic situations and domestic production levels. The former is due to good circulations of the world economy and China's entry into WTO, which lead to substantial materials input but a lack of efficiency advancements. The latter is owing to policy steering of the eleventh five-year plan unveiled in 2005, which drives the movement of technical improvement, renewable energy development, wastes recycling, and multilevel using. But we have to admit that China still has to go a long way to pursue fossil fuel productivity compared with countries like Japan and Germany.

MFA accounting system calculates environmental pressure produced by the resource depletion. Its standpoint is payments for import only cover the economic costs without environmental costs as well as hidden flows value in the process of energy production. By this token, one country can pass over the environmental cost by importing so as to reduce the domestic natural risk. From this point of view, it is necessary to shift energy strategy from export-oriented to import-oriented style and elevate the export price by considering environmental expense and enlarging import proportion, from which home resource and environment can be protected in a qualified sense. Nevertheless, it is myopia for a particular developing period in certain regions, but not beneficial for universal sustainable utility of resource. Natural wealth belongs to human beings, without boundary of different nations and territories.

5. Discussions and Prospects

For the existing energy supply and demand status quo, more efforts are needed to intensify energy structure reforms, though the expansion of gas domestic output and import quotation provided a new perspective. Furthermore, the unchanged conditions may be related to the existing exploitation patterns, the history of coal mining and technical problems in the development of pelagic natural gas, which are primarily reasons for the univocal energy current situation. Whereas, the future structure of energy utility will move forward to a rational and sustainable direction as long as technical progress, sufficient facilities, financing of safeguards, and national supporting policies are provided.

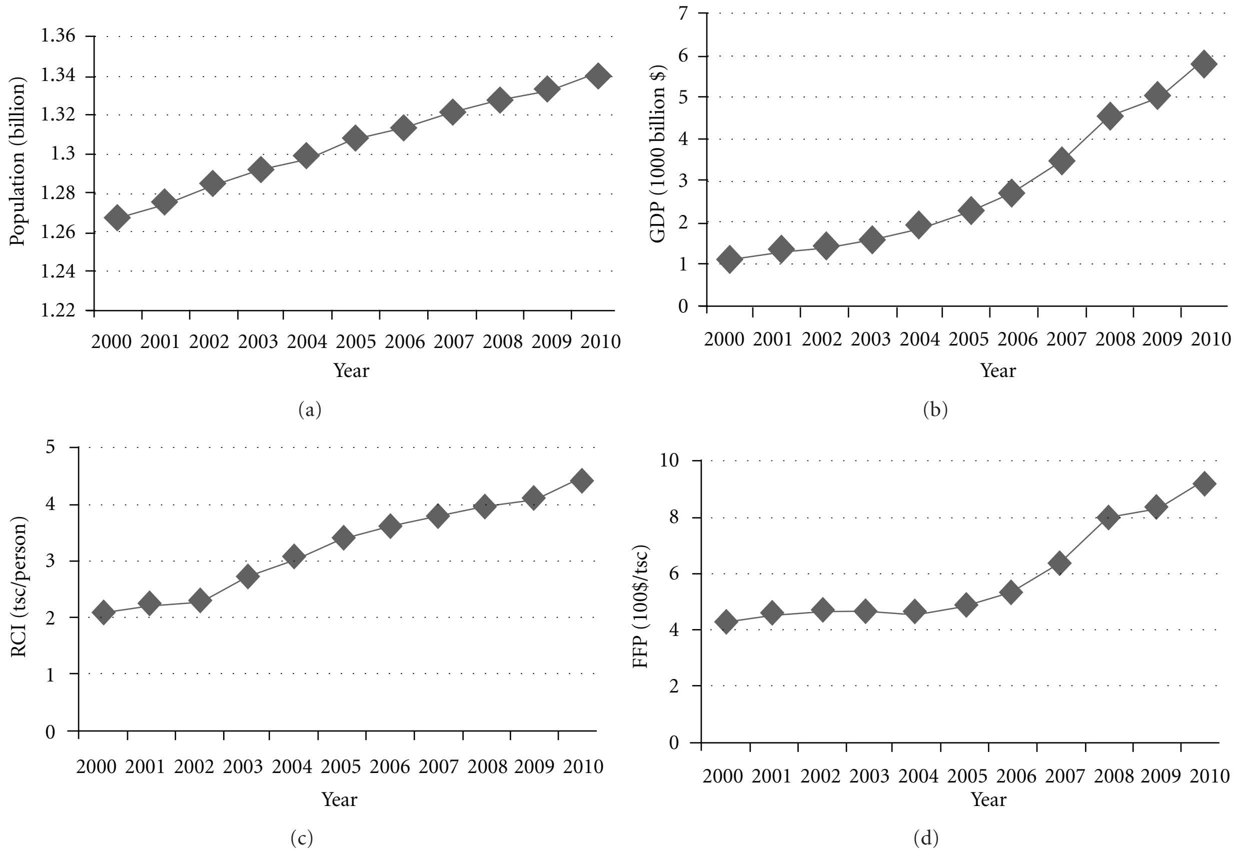

Figure 2: A comprehensive index comparison of fossil fuels in China during 2000–2010.

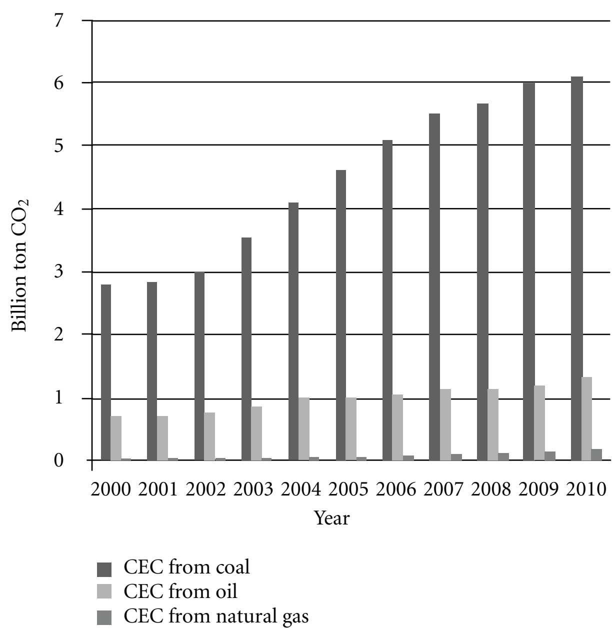

Figure 3: CEC amount from three types of fossil fuels from 2000 to 2010 in China.

Table 7: Statistics of FFP in other countries during recent years (Unit: \$/tsc).

Country	1975	1980	1985	1990	1995	1996
Austria	649.9	887.8	620.3	1197.9	1415.7	1362.2
Germany	649.8	984.6	751.6	1451.6	1296.6	1313.9
Japan	472.1	700.6	852.8	1410.2	2543.3	2255.7
Netherlands	460.5	670.9	437.1	884.2	1018	949.1
Great Britain	1487.01	1714.01	1012	1517.1	1482.2	1513.2

Meanwhile, the "closed material cycle mode" that with the process of "energy production → energy consumption → recycled energy → recycled energy reuse" should be extensively implemented in extensive energy based industries in order to decrease the C/S ratio value and create more economic value by consuming the previous amount of energy consumption. And the bundled infrastructures or strategies should be followed up, for example, the generalization of garbage classification with recycled waste energy appliance, popularization of new energy vehicle service facilities.

The transformation of GDP has necessary connections with the resource consumption intensity and the fossil fuel productivity. To accomplish the target of energy saving and emission reducing, and also to keep to the path of sustainable development, it is necessary to rely on domestic research and developments as well as global introductions of advanced technology in enhancing efficiency and reduced consumption for internal upswing.

Apparently, material and energy streams are dependent with each other in a different manner, so the simplex material flow analysis is not comprehensive in identifying the energy consumption in an environmental economic system. Next, we should combine the material and energy analysis to understand the social metabolism of fossil fuels from all angles. At the same time, the indexes and their variation trends provide reasonable explanations for future policy drafts in energy saving and emission reducing by evaluating the recent 11 years' resource consumption and production efficiency.

Acknowledgments

This study was supported by the National Science Foundation for Innovative Research Group (no. 51121003), Key Program of National Natural Science Foundation (no. 50939001 and 41271543), and Program for New Century Excellent Talents in University (NCET-09-0226). The authors are especially grateful for the financial support from Beijing Development Area Co., Ltd.

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The Scientific World Journal
Volume 2012, Article ID 310407, 10 pages
doi:10.1100/2012/310407

Research Article

Industry Efficiency and Total Factor Productivity Growth under Resources and Environmental Constraint in China

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Received 7 September 2012; Accepted 20 November 2012

Academic Editors: J. L. Míguez, A. Piacentino, D. M. F. Santos, and S. K. Tyagi

The growth of China's industry has been seriously depending on energy and environment. This paper attempts to apply the directional distance function and the Luenberger productivity index to measure the environmental efficiency, environmental total factor productivity, and its components at the level of subindustry in China over the period from 1999 to 2009 while considering energy consumption and emission of pollutants. This paper also empirically examines the determinants of efficiency and productivity change. The major findings are as follows. Firstly, the main sources of environmental inefficiency of China's industry are the inefficiency of gross industrial output value, the excessive energy consumption, and pollutant emissions. Secondly, the highest growth rate of environmental total factor productivity among the three industrial categories is manufacturing, followed by mining, and production and supply of electricity, gas, and water. Thirdly, foreign direct investment, capital-labor ratio, ownership structure, energy consumption structure, and environmental regulation have varying degrees of effects on the environmental efficiency and environmental total factor productivity.

1. Introduction

Great achievements have been made in China's economy during the past three decades of reform and opening up. However, with rapid economic growth, the depletion of natural resources and the environmental degradation have become increasingly prominent. Based on a forecast for 2005–2035, China is to replace the USA as the world's leading embodied energy consumer in 2027, when its per capita energy consumption will be one quarter of that of the USA [1]. What's more, the total cost of environmental degradation and ecological damage reached about 2037 billion US dollars, accounting for 3.8% of the gross domestic product (GDP) in 2009 [2]. The problems of resources and environment not only have brought huge losses to China's economic and social development, but also may directly lead to unsustainable development in the future. Therefore, the 12th five-year plan of China request policy makers promote the coordination and sustainability of economic development. In addition, carbon emissions associated with industry transfer and international trades are illustrated in terms of impacts on global climate policies [3], so the globalization also promotes China to pay more emphasis on energy saving and environment protection.

In much of the contemporary literature, researchers have been studying the changes in China's efficiency and productivity and their influence on economic growth and transformation from various perspectives. Nevertheless, with increasingly prominent problems of resources and environment in the process of economic development, a growing number of researchers believe that resources and environment are not only endogenous variables, but also rigid constraints on economic development [4, 5]. Therefore, when evaluating economic performance by total factor productivity (TFP), it is necessary to consider the resource and environmental factors which have tremendous impacts on economic development as well as a traditional factors such as capital and labor. In fact, resource and environmental factors have been added into efficiency and productivity analysis framework to reestimate China's economic growth efficiency and TFP in recent literature which draws many valuable conclusions [6–9].

However, among these literatures, most of their data are based on subprovincial level in China, and very few of them are carried out from the subindustrial level in China. As Jorgenson and Stiroh [10] pointed out that economic growth is obviously different among sectors and industries, we should use subindustry data to describe the panorama of economic growth. In addition, due to less output potential loss for all the allocation alternatives, the sector regulation strategy is shown to be more effective than the province regulation strategy [11]. The rapid growth of China's industry highly depends on energy and environment, and industry plays the most important role in the energy saving and emission reduction of national economy. Therefore, it is significantly necessary to measure the costs of energy and environment.

Since traditional distance function cannot estimate the harmful effects of environmental pollution, many studies use indirect methods to calculate TFP with the consideration of pollutant emissions, which is obviously too simplified. Some researchers use radical and oriented data envelopment analysis (DEA) to compute directional distance function in order to simulate the harmful effects of environmental pollution, but this method will overestimate the efficiency of the evaluation object [12]. In contrast, nonradical and nonoriented directional distance function which is slack-based measure (SBM) and Luenberger productivity index can overcome the above deficiencies in the measurement of environmental efficiency and environmental TFP [13, 14].

In addition, only one or several bad or undesirable outputs have been considered in the existing literature. However, for China's industry at this stage, all energy inputs and pollutant emissions should be taken into account, by which environmental efficiency and environmental TFP can reflect the quality contribution to economic growth more precisely [15].

Therefore, on the basis of existing literature, this paper aims to use SBM directional distance function to measure environmental efficiency and its components of 36 subindustries of China's industry, use SBM directional distance function and the Luenberger productivity index to measure the environmental TFP and its components, then test, and compare the differences of the determinants' impacts.

2. Model Specification

Different from the traditional production function, production technology considering energy and environment must reflect resource saving and environmental protection. Since resources can be introduced into productivity analysis framework as traditional inputs (such as capital and labor), the difficulty of constructing production frontier function is how to take environmental factors into account. In order to combine energy and environment factors with traditional economic factors (capital, labor, and output), according to Färe et al. [16], this paper considers every subindustry of China's industry as a decision making unit (DMU) and construct the optimal production frontier of each period. It is assumed that there are N kinds of inputs $x = (x_1, \dots, x_N) \in R_N^+$ in every subindustry, M kinds of good outputs $y = (y_1, \dots, y_M) \in R_M^+$, and I kinds of bad or undesirable outputs $b = (b_1, \dots, b_I) \in R_I^+$. Then, at the stage of $t = (1, \dots, T)$, the subindustry of $k = (1, \dots, K)$, the input and output vectors are $(x^{t,k'}, y^{t,k'}$, and $b^{t,k'})$, and the weight for each section of observation value is λ_k^t. Using data envelopment analysis (DEA), the environmental technology model is given by

$$\begin{aligned} P^t(x^t) &= \Bigg\{ (y^t, b^t) : \sum_{k=1}^{K} \lambda_k^t y_{km}^t \ge y_{km}^t, \forall m; \sum_{k=1}^{K} \lambda_k^t b_{ki}^t = b_{ki}^t, \\ &\qquad \forall i; \sum_{k=1}^{K} \lambda_k^t x_{kn}^t \le x_{kn}^t, \forall n; \sum_{k=1}^{K} \lambda_k^t = 1, \lambda_k^t \ge 0, \forall k \Bigg\}. \end{aligned} \tag{1}$$

Because production frontier of every subindustry may lead to nonoptimal scale of production when considering imperfect competition and externality, a restriction is defined as $\sum_{k=1}^{K} \lambda_k^t = 1$, meaning that the production frontier reflects the hypothesis of variable returns to scale (VRS); If the restriction $\sum_{k=1}^{K} \lambda_k^t = 1$ is removed, then all firms can produce under the conditions of optimal scale, which means the production frontier reflects the hypothesis of constant returns to scale (CRS).

2.1. SBM Directional Distance Function. According to Fukuyama and Weber [14], SBM directional distance function considering resources and environment is defined as

$$\begin{aligned} &\vec{S}_V^t \left(x^{t,k'}, y^{t,k'}, b^{t,k'}, g^x, g^y, g^b \right) \\ &\quad = \max_{s^x, s^y, s^b} \frac{(1/N) \sum_{n=1}^{N} (s_n^x / g_n^x)}{2} \\ &\qquad + \frac{(1/(M+I)) \left[\sum_{m=1}^{M} \left(s_m^y / g_m^y \right) + \sum_{i=1}^{I} \left(s_i^b / g_i^b \right) \right]}{2} \\ &\qquad \text{s.t.} \sum_{k=1}^{K} \lambda_k^t x_{kn}^t + s_n^x = x_{k'n}^t, \quad \forall n; \\ &\qquad \sum_{k=1}^{K} \lambda_k^t y_{km}^t - s_m^y = y_{k'm}^t, \quad \forall m; \\ &\qquad \sum_{k=1}^{K} \lambda_k^t b_{ki}^t + s_i^b = b_{k'i}^t, \quad \forall i; \\ &\qquad \sum_{k=1}^{K} \lambda_k^t = 1, \lambda_k^t \ge 0, \forall k; s_n^x \ge 0, \quad \forall n; \\ &\qquad s_m^y \ge 0, \quad \forall m; \quad s_i^b \ge 0, \quad \forall i, \end{aligned} \tag{2}$$

where $\vec{S}_V^t$ denotes the directional distance function under VRS. If the weight variable and the constraint of 1 are removed, then $\vec{S}_c^t$ is a directional distance function under

CRS; ($x^{t,k'}$, $y^{t,k'}$, and $b^{t,k'}$) refer to the input vector of each subindustry, good output vector, and bad or undesirable output vector; (g^x, g^y, and g^b) represent the direction vector of input compression, good output expansion, and bad or undesirable output compression; (s_n^x, s_m^y, and s_i^b) denote the slack variable of input, good output and bad or undesirable output; Slack variable measures observations' deviation from the production frontier, therefore (s_n^x, s_m^y, and s_i^b) indicates excessive use of inputs, underproduction of good outputs, and excessive emission of bad or undesirable outputs. Therefore, the target function is to maximize the sum of input-inefficiency average and output-inefficiency average. According to Cooper et al. [12], the above technical inefficiency can be decomposed as.

Inputs inefficiency:

$$IE_x = \frac{1}{2N}\sum_{n=1}^{N}\frac{s_n^x}{g_n^x}. \tag{3}$$

Good outputs inefficiency:

$$IE_y = \frac{1}{2(M+L)}\sum_{m=1}^{M}\frac{s_m^y}{g_m^y}. \tag{4}$$

Bad or undesirable outputs inefficiency:

$$IE_b = \frac{1}{2(M+L)}\sum_{l=1}^{L}\frac{s_l^b}{g_l^b}. \tag{5}$$

2.2. Luenberger Productivity Index. According to the existing literature, there are three main indexes to measure productivity: Malmquist index extended by Färe et al. [17], Luenberger productivity index developed by Chambers et al. [18], and Malmquist-Luenberger productivity index extended by Chung et al. [19]. Compared with Malmquist index and Malmquist-Luenberger productivity index, Luenberger productivity index does not need to choose the measuring orientation and make change in equal proportion. Therefore, Luenberger productivity index is more suitable for measuring the environmental efficiency and the environmental TFP which accounts for energy input and pollution emission.

According to Chambers et al. [18], Luenberger productivity index between stage t and $t+1$ is

$$\begin{aligned}\mathrm{LTFP}_t^{t+1} &= \frac{1}{2}\Big\{\Big[\vec{S}_C^{t}(x^t,y^t,b^t;g) - \vec{S}_C^{t}(x^{t+1},y^{t+1},b^{t+1};g)\Big] \\ &\quad+\Big[\vec{S}_C^{t+1}(x^t,y^t,b^t;g) - \vec{S}_C^{t+1}(x^{t+1},y^{t+1},b^{t+1};g)\Big]\Big\}.\end{aligned} \tag{6}$$

Following Grosskopf [20], Luenberger productivity index can be further decomposed into pure efficiency change (LPEC), pure technical progress (LPTP), scale efficiency change (LSEC), and technical progress scale change (LTPSC)

$$\begin{aligned}
&\mathrm{LTFP} = \mathrm{LPEC} + \mathrm{LPTP} + \mathrm{LSEC} + \mathrm{LTPSC},\\
&\mathrm{LPEC}_t^{t+1} = \vec{S}_v^{t}(x^t,y^t,b^t;g) - \vec{S}_v^{t+1}(x^{t+1},y^{t+1},b^{t+1};g),\\
&\mathrm{LPTP}_t^{t+1}\\
&\quad= \frac{1}{2}\Big\{\Big[\vec{S}_v^{t+1}(x^t,y^t,b^t;g) - \vec{S}_v^{t}(x^t,y^t,b^t;g)\Big]\\
&\qquad+\Big[\vec{S}_v^{t+1}(x^{t+1},y^{t+1},b^{t+1};g) - \vec{S}_v^{t}(x^{t+1},y^{t+1},b^{t+1};g)\Big]\Big\},\\
&\mathrm{LSEC}_t^{t+1}\\
&\quad= \Big[\vec{S}_C^{t}(x^t,y^t,b^t;g) - \vec{S}_V^{t}(x^t,y^t,b^t;g)\Big]\\
&\qquad- \Big[\vec{S}_C^{t+1}(x^{t+1},y^{t+1},b^{t+1};g) - \vec{S}_V^{t+1}(x^{t+1},y^{t+1},b^{t+1};g)\Big],\\
&\mathrm{LTPSC}_t^{t+1}\\
&\quad= \frac{1}{2}\Big\{\Big[\Big(\vec{S}_C^{t+1}(x^t,y^t,b^t;g) - \vec{S}_V^{t+1}(x^t,y^t,b^t;g)\Big)\\
&\qquad-\Big(\vec{S}_C^{t}(x^t,y^t,b^t;g) - \vec{S}_V^{t}(x^t,y^t,b^t;g)\Big)\Big]\\
&\qquad+\Big[\Big(\vec{S}_C^{t+1}(x^{t+1},y^{t+1},b^{t+1};g)\\
&\qquad-\vec{S}_V^{t+1}(x^{t+1},y^{t+1},b^{t+1};g)\Big)\\
&\qquad-\Big(\vec{S}_C^{t}(x^{t+1},y^{t+1},b^{t+1};g)\\
&\qquad-\vec{S}_V^{t}(x^{t+1},y^{t+1},b^{t+1};g)\Big)\Big]\Big\}.
\end{aligned} \tag{7}$$

When the above five values are greater than 0, they, respectively, indicate the productivity improvement, efficiency improvement, technical progress, scale efficiency improvement, and technical deviation CRS, conversely reverses. While it is necessary to use eight directional distance functions to decompose Luenberger productivity index, four of them belong to CRS hypothesis, and the other four are estimated under the condition of VRS hypothesis.

3. Measurement of Environmental Efficiency and Environmental TFP

3.1. Outputs and Inputs

3.1.1. Outputs

Good Outputs. industrial output is the most important good outputs, and it refers to gross industrial output value of 36 subindustries over the period from 1999 to 2009, which can be obtained from China Statistical Yearbook, published by National Bureau of Statistics of China (NBSC) [21]. The data should be transformed as 1990's constant price according to the producer price index (PPI) for manufactured goods.

Undesirable Outputs. considering the emissions of industrial pollutants, the bad or undesirable outputs should consist of industrial wastewater, carbon dioxide, sulfur dioxide, and solid waste. Emissions of wastewater, sulfur dioxide, and solid waste of each subindustry can be collected from NBSC. Unfortunately, there is no data of carbon dioxide emissions from NBSC, so this study follows Chen's methods [15] to use the reference approach in the Guidelines for National Greenhouse Gas Inventories provided by Intergovernmental Panel on Climate Change (IPCC) in 2006. Carbon dioxide emissions could be calculated as

$$C_t = \sum_{i=1}^{3} C_{i,t} = \sum_{i=1}^{3} E_{i,t} \times \mathrm{NCV}_i \times \mathrm{CEF}_i \times \mathrm{COF}_i \times \left(\frac{44}{12}\right). \quad (8)$$

Here, the emissions of carbon dioxide are denoted by C, the types of primary energy (coal, oil, and natural gas) by $I = (1, 2, 3)$, the consumption of energy by E. Meanwhile, NCV represents the average net calorific value of the primary energy obtained from China Energy Statistics Yearbook published by NBSC [22]. CEF represents the carbon emission factor provided by IPCC; COF represents the carbon oxidation factor; 44 and 12 correspond, respectively, to the molecular weight of carbon dioxide and carbon.

3.1.2. Inputs. Energy input should be considered as important as capital and labor. In the light of the majority of literature, this paper takes the number of employees every year as labor input and the energy consumption as energy input in subindustries, both of which can be inquired from NBSC [18]. Capital stock is one of the most important inputs, but NBSC does not provide details of the capital stock data; therefore, capital stock data need to be estimated. This paper estimates industry capital stock data with the method of perpetual inventory. Obviously, the calculation of capital stock of each year should be based on the capital stock of base year, depreciation rate, and constant price of investment. Following Chen's method [15], this study gets capital stock of 1980 as capital stock of the base year. The depreciation rates of subindustry are estimated with the data of depreciation value and fixed assets value from Chinese Statistical Yearbook and Chinese Industry Economy Statistical Yearbook published by NBSC [23]. This paper constructs the investment sequence data based on the difference of fixed assets and then converts them to constant price of 1990 by the investment price index of each year. After that, with the perpetual inventory method, capital stock data of various subindustries are calculated over the period from 1999 to 2009.

3.2. Environmental Efficiency and Its Components. Based on SBM directional distance function and Luenberger productivity index, this paper measures the environmental efficiency and environmental TFP by the software package Excel Solver Prem Platform V5.5 which is widely used in the present study. Environmental inefficiency values of every subindustry under the assumption of CRS and VRS are measured, respectively, and the results are given in Table 1.

Since the environmental efficiency value under VRS assumption does not consider scale efficiency, the value under VRS assumption must be lower than CRS assumption, which is confirmed in Table 1. Under CRS assumption industrial production is in the conditions of optimal scale. However, many factors such as imperfect competition and externality may lead to nonoptimal scale. Therefore, when the value under CRS assumption is different from that under VRS assumption, the task is to analyze the efficiency under VRS assumption [24]. This study will focus on the analysis of environmental efficiency and its components under VRS assumption.

The total value of environmental inefficiency of China's industry is 60.8%. The main source of environmental inefficiency is the inefficiency of gross industrial output value (14.7%), followed by the inefficiency of energy consumption (10.7%), capital stock (7.1%), SO_2 (6.7%), solid waste (6.7%), CO_2 (6.5%), and wastewater (5.7%), and the inefficiency value of employee (2.6%) is far lower than other outputs and inputs. Therefore, the keys of improvement of environmental efficiency are growth of industrial output, energy saving and reduction of pollutant emissions.

In order to show the difference of environmental efficiency among subindustries due to industrial characteristics, this study classifies 36 two-digit code industries into three categories according to industrial classification standards provided by NBSC. The three industrial categories are mining, manufacturing, and production and supply of electricity, gas, and water. Table 1 shows that the highest environmental inefficiency value is mining (66.3%), followed by production and supply of electricity, gas, and water (59.6%) and manufacturing (56.5%). Inefficiency of gross industrial output value, energy consumption, and pollution emissions are the main sources of these three categories' environment inefficiency. The environmental inefficiency value of gross industrial output value of mining (19.5%) and production and supply of electricity, gas and water (16.6%) are much higher than manufacturing (7.9%). The inefficiency value of energy consumption of all three categories is more than 10%, which indicates that the task of energy saving of China's industry is very heavy.

3.3. Environmental TFP and Its Components. The environmental TFP and its components are given in Table 2. The mean value of environmental TFP of China's industry over the period from 1999 to 2009 is 4.51%; in other words, the environmental efficiency of China's industry increased by 4.51% each year. This result is obviously lower than the traditional TFP without considering energy input and pollution outputs. About the components, the pure efficiency change is −3.69%, pure technical progress is 4.93%, scale efficiency change is 2.88%, and technical progress scale change is 0.39%. It means that technological innovation denoted by pure technical progress makes significant contributions to the improvement of the environmental TFP of China's

Table 1: Environmental inefficiency and its components of China's industry.

Category	Industry	Gross industrial output value	Capital stock	Number of employee	Energy consumption	Waste water emission	CO_2 emission	SO_2 emission	Solid waste emission	Total value
VRS	Mining	0.195	0.051	0.012	0.119	0.057	0.07	0.076	0.083	0.663
	Manufacturing	0.079	0.068	0.053	0.101	0.060	0.068	0.071	0.065	0.565
	Production and supply of electricity, gas, and water	0.166	0.095	0.013	0.102	0.054	0.057	0.055	0.054	0.596
	Mean value	0.147	0.071	0.026	0.107	0.057	0.065	0.067	0.067	0.608
CRS	Mining	0.249	0.064	0.04	0.123	0.061	0.089	0.081	0.086	0.794
	Manufacturing	0.124	0.088	0.075	0.126	0.067	0.085	0.085	0.081	0.734
	Production and supply of electricity, gas, and water	0.257	0.128	0.023	0.145	0.08	0.085	0.073	0.076	0.867
	Mean value	0.209	0.093	0.046	0.131	0.069	0.086	0.079	0.081	0.798

Table 2: Environmental TFP and its components of China's industry.

Industry	LTFP	LPEC	LPTP	LSEC	LTPSC
Mining					
Mining and washing of coal	0.031	−0.1199	0.0975	0.2151	−0.1618
Extraction of petroleum and natural gas	0.0027	−0.2863	0.2561	0.0612	−0.0283
Mining and processing of ferrous metal ores	0.1022	−0.1191	0.0561	0.1826	−0.0175
Mining and processing of nonferrous metal ores	0.1025	−0.0137	0.061	0.0485	0.0067
Mining and processing of nonmetal ores	0.0348	0.0044	0.0535	−0.0242	0.0011
Mean	0.0546	−0.1069	0.1048	0.0966	−0.0399
Manufacturing					
Processing of food from agricultural products	0.0573	−0.0075	0.0264	0.0781	−0.0397
Manufacture of foods	0.0529	−0.0067	0.0586	−0.0158	0.0167
Manufacture of beverages	0.0425	−0.0019	0.04	0.004	0.0005
Manufacture of tobacco	0.0997	0.0294	−0.0415	0.0139	0.0979
Manufacture of textile	0.0227	−0.012	0.0441	−0.0183	0.0090
Manufacture of textile wearing apparel, footware, and caps	0.0247	−0.0317	0.0408	0.0246	−0.009
Manufacture of leather, fur, feather, and related products	0.0089	−0.0212	0.0209	0.0014	0.0078
Processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products	0.0222	−0.0134	0.026	0.0082	0.0014
Manufacture of furniture	0.0870	−0.0173	−0.0830	0.0895	0.0978
Manufacture of paper and paper products	0.0117	−0.0004	0.0502	−0.0963	0.0581
Printing and reproduction of recording media	0.0450	0.0289	−0.0353	0.0168	0.0346
Manufacture of articles for culture, Education, and sport activities	0.0558	0.0034	−0.1198	−0.0533	0.2254
Processing of petroleum, coking, and processing of nuclear fuel	0.0104	−0.0146	0.0444	−0.0487	0.0293
Manufacture of raw chemical materials and chemical products	0.0587	−0.0035	0.0412	0.016	0.0051
Manufacture of medicines	0.0272	−0.0058	0.0182	0.0228	−0.008
Manufacture of chemical fibers	0.0187	0.0025	0.0216	−0.0027	−0.0026
Manufacture of rubber	0.0213	−0.009	0.0265	0.0034	0.0004
Manufacture of plastics	0.0859	−0.0656	0.058	0.054	0.0395
Manufacture of nonmetallic mineral products	0.0755	−0.0094	0.0943	−0.0491	0.0398
Smelting and pressing of ferrous metals	0.0893	0.0093	0.0534	0.0219	0.0047
Smelting and pressing of nonferrous metals	0.0494	−0.0038	0.038	0.0228	−0.0076
Manufacture of metal products	0.0219	−0.0172	0.0287	0.0188	−0.0084
Manufacture of general purpose machinery	0.0783	0.0237	0.0532	−0.0009	0.0023
Manufacture of special purpose machinery	0.0516	0.0006	0.0579	−0.0034	−0.0035
Manufacture of transport equipment	0.0457	0.0035	0.0354	0.0066	0.0002
Manufacture of electrical machinery and equipment	0.0756	−0.0399	0.0954	0.0123	0.0079
Manufacture of communication equipment, computers, and other electronic equipment	0.1757	0.0014	0.0925	0.0534	0.0284
Manufacture of measuring instruments and machinery for cultural activity and office work	0.1463	0.0332	0.0216	0.0900	0.0014
Mean	0.0558	−0.0052	0.0288	0.0096	0.0225
Production and supply of electricity, gas, and water					
Production and supply of electric power and heat power	0.0317	0.0144	0.0145	−0.0574	0.0603
Production and supply of gas	0.0703	0.0101	0.0176	0.0169	0.0257
Production and supply of water	−0.0273	−0.0200	0.0104	−0.0195	0.0018
Mean	0.0249	0.0015	0.0142	−0.0200	0.0293
Total mean	0.0451	−0.0369	0.0493	0.0288	0.0039

industries. Therefore, technological innovation is the main driving factor of upgrading and sustainable development of China's industry. While the contribution of pure efficiency change is negative, and the contribution of technical progress scale change is small.

The mean value of environmental TFP of mining is 5.46%, which is much higher than production and supply of electricity, gas, and water (2.49%), but lower than manufacturing (5.58%). Pure efficiency change and pure technical progress make the greatest contribution to the environmental TFP of mining; the mean values of which are 10.48% and 9.66%, respectively.

The main source of improvement of environmental TFP of manufacturing is pure technical progress and technical progress scale change; the mean values of which are 2.88% and 2.25%, respectively. Among the 28 subindustries of manufacturing, the value of environmental TFP of manufacture of communication equipment, computers and other electronic equipment (17.57%) is the highest, followed by manufacture of measuring instruments and machinery for cultural activity and office work (14.63%). Pure technical progress makes the greatest contribution to the former's environmental TFP, while scale efficiency change makes the greatest contribution to the latter's environmental TFP. The environmental TFP of some industries is very low, less than 2%, such as manufacture of leather, fur, feather and related products, manufacture of paper and paper products, processing of petroleum, coking, processing of nuclear fuel, and manufacture of chemical fibers, most of which are pollution-intensive industries.

Because of the negative value of scale efficiency change and low value of pure efficiency change, the mean value of environmental TFP of production and supply of electricity, gas, and water is much lower than that of manufacturing and mining.

4. Determinants of Environmental Efficiency and Environmental TFP

4.1. Data. What determines the environmental efficiency and environmental TFP of China's industry? Loko and Diouf fully analysed the determinants of productivity growth [25]. Based on the recent literature and context of China's economic transformation, the most important determinants of environmental efficiency and environmental TFP are as follows.

4.1.1. Capital Structure (X_1). Capital structure is denoted by the proportion of value-added of foreign direct investment (FDI) enterprises in the added value of industrial enterprises above designated size. China has received significant FDI inflows for the past three decades, and FDI has been an important factor influencing industrial efficiency and productivity growth. Zhou et al. pointed out that domestic firms in industries which have more FDI or have a longer history of FDI tend to have lower productivity [26]. Estimating the influence of FDI on efficiency and TFP of China's industry under resources and environment constraint is actually a test of "pollution haven hypothesis" [27].

4.1.2. Endowment Structure (X_2). Endowment structure is denoted by capital-labor ratio. Capital and labor are sources of comparative advantage for most industries. The rising of capital-labor ratio means capital deepening which is an important determinant of industrial efficiency and productivity growth. Empirical studies show that the elasticity of substitution between capital and labor is larger than the one in developed countries but smaller than that in developing countries [28]. There are, however, several aspects of China's industrial strategy that have partially offset the trend toward capital deepening [29]. Therefore, this paper attempts to test the influence of capital deepening on efficiency and productivity under resources and environment constraint.

4.1.3. Ownership Structure (X_3). Ownership structure is denoted by the proportion of added value of state-owned enterprises (SOEs) covering the total added value of industrial enterprises above designated size. At the outset of the transition towards a market economy, the governments in developing countries envisioned that privatization would be an efficient way to improve performance and productivity. The reform of state-owned enterprises has greatly affected the profitability and productivity of Chinese industrial firms [30]. Incentive mechanism based on property rights may determine the environmental efficiency and environmental TFP through imperfect competition and pollution externality.

4.1.4. Energy Consumption Structure (X_4). Energy consumption structure is denoted by the proportion of electricity consumption accounted for total energy consumption. Different kinds of energy have different costs and pollution emissions which will influence the environment efficiency and environmental TFP.

4.1.5. Intensity of Environmental Regulation (X_5). China has adopted various policy measures to control industrial pollution. We need to assess the impact of pollution regulations on industrial productivity. Using the method of composite index, this paper builds a complex measurement system of China's industrial intensity of environmental regulation. This system has a target layer (intensity of environmental regulation) and three evaluation layers (waste water, waste gas, and solid waste).

The main data sources are China Statistical Yearbook, China Energy Statistics Yearbook, Chinese Industry Economy Statistical Yearbook, and China Economic Census Yearbook published by NBSC [21–23, 31]. Some individual missing values are supplemented by linear interpolation. As the lower value of environmental inefficiency indicates higher environmental efficiency, in order to make the regression results consistent with the tradition, we use the formula $E = 1/(1 + IE)$ to transform values of environmental inefficiency into values of environmental efficiency. Since the transformation value is between 0 and 1, we should

Table 3: Estimation results of environmental efficiency and environmental TFP[a].

Variable	Coefficient estimates		
Predictor	Environmental efficiency		Environmental TFP
	VRS	CRS	
Intercept	3.393 (3.334)***	2.283 (2.209)***	2.561 (3.227)***
X_1	−7.234 (−6.789)***	−7.583 (−7.968)***	−8.821 (−10.271)***
X_2	0.16 (2.968)***	0.158 (1.260)	0.172 (3.234)***
X_3	2.747 (0.994)	2.969 (1.227)	3.066 (3.485)***
X_4	15.031 (6.092)***	16.213 (6.256)***	15.615 (7.162)***
X_5	−0.157 (−2.314)**	−0.196 (−2.206)**	0.034 (5.413)***
R^2 (sigma)	0.064	0.035	0.894
Observations	396	396	360

[a]The standard errors of coefficient estimates are in parentheses. ** and *** denote significance at 5% and 1% levels, respectively.

choose the Tobit regression model. At the same time, because the environmental TFP should be analyzed dynamically and LTFP index is compared with last year, it is essential to transform the four types of index above into cumulative growth index taking 1999 as the base period. Because some values are negative, according to Managi and Jena [32], all values should be added one, and then the values through logarithmic transformation can be used as the dependent variable of the model.

4.2. Estimation Results. The estimation results are given in Table 3. Hausman test shows that it's better to choose fixed effect model.

Capital structure (X_1) has a negative effect on both environmental efficiency and environmental TFP, that is to say, the increase of FDI reduced the industrial environmental efficiency and environmental TFP level; "pollution haven hypothesis" gets the verification here.

The coefficients of capital labor ratio (X_2) except the regression in CRS assumption are positive and significant, which indicates that capital deepening of China's industry can accelerate technological innovation and promote energy saving and emission reduction.

The coefficients of ownership structure (X_3) are not significant both for VRS hypothesis and the CRS hypothesis, but the ownership structure has significantly positive influence on environmental TFP. The estimation result indicates that the influence of ownership depends on complex factors and is not easy to be expected.

The coefficients of energy consumption structure (X_4) have significantly positive influence on environmental efficiency and environmental TFP. While the electricity consumption increased by 1%, the environmental efficiency and environmental TFP increased by more than 15%. The empirical results show that compared with coal, petroleum, and other fossil energy, electricity is clean energy, which can greatly improve China's efficiency and productivity under resource and environmental constraints.

Environmental regulation intensity (X_5) has a negative impact on the environmental efficiency under the hypotheses of VRS and CRS, but positive impact on the environmental TFP. This empirical result shows that environmental regulation will increase enterprise production costs and lead the environmental regulation and enterprise competitiveness to be in a dilemma in the short term.

5. Conclusions and Policy Implications

Using SBM directional distance function and Luenberger productivity index, this paper measures the environmental efficiency, environmental TFP, and its components at the level of subindustry in China over the period from 1999 to 2009 and tests the impacts of industrial capital structure, endowment structure, ownership structure, energy consumption structure, and intensity of environmental regulation. The findings of this study are crucial for environment administration and industrial upgrading. The specific policies are suggested as follows.

5.1. Optimizing Industrial Structure. Considering the fact that both environmental efficiency and environmental TFP are different among subindustries, the government should accelerate the development of high-tech industries and environment friendly industries and limit the development of pollution-intensive industries and energy-intensive industries. The policy makers should also make vigorous guidance to draw FDI to high-tech industries and environmental-friendly industries and promote the industrial upgrading of FDI, protecting China from the pollution heaven of FDI.

5.2. Promoting Technological Innovation on Energy Saving and Emission reduction. Excessive energy consumption and pollutant emissions are the main sources of environmental inefficiency of China's industry. Technological innovation makes significant contributions to the improvement of the environmental TFP of China's industry. It is necessary to increase research investment to develop environmental technology, energy saving technology, low-carbon technology, and so on.

5.3. Improving Energy Consumption Structure. The government should make policies to promote industrial enterprises to reduce fossil energy consumption including coal and petroleum and improve the proportion of electricity consumption. It is also absolutely essential to vigorously develop clean energy such as nuclear, hydraulic, wind, and solar power.

5.4. Establishing Energy and Environment Regulation Policies of Incentive Compatibility. The regulation strategies based on sectors are better than those based on provinces in terms of regulation costs [11]. The emphases of regulation should be shifted to sectors in the short term and take market-oriented instruments of regulation (e.g., prices and taxes) in the long term and especially promote market-oriented reform of electricity and oil industry. The government also should strengthen the pollution control on pollution-intensive industries, such as power production, nonmetallic manufacturing, ferrous metallurgy, paper manufacturing, food processing, and chemical industries which discharge lots of SO_2 and COD.

Acknowledgments

This study has been supported by the National Nature Science Foundation of China (Grant nos. 71002086, 71203224) and the Fundamental Research Funds for the Central Universities (Grant no. 12JNQM010).

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The Scientific World Journal
Volume 2012, Article ID 858103, 5 pages
doi:10.1100/2012/858103

The ScientificWorldJOURNAL

Research Article

Embodied Energy Use in China's Infrastructure Investment from 1992 to 2007: Calculation and Policy Implications

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Received 8 October 2012; Accepted 22 November 2012

Academic Editors: B. Chen, Z.-M. Chen, and H.-S. Tang

Infrastructure has become an important topic in a variety of areas of the policy debate, including energy saving and climate change. In this paper, we use an energy input-output model to evaluate the amounts of China's embodied energy use in infrastructure investment from 1992 to 2007. We also use the structure decomposition model to analyze the factors impacting the embodied energy use in infrastructure investment for the same time period. The results show that embodied energy use in infrastructure investment accounted for a significant proportion of China's total energy use with an increasing trend and reflect that improper infrastructure investment represents inefficient use of energy and other resources. Some quantitative information is provided for further determining the low carbon development potentials of China's economy.

1. Introduction

During the last three decades, China's remarkable economic growth not only has enabled it to achieve social progress, but also has been accompanied by a corresponding surge in energy use (Figure 1). Although China has successfully declined its energy intensity (energy consumption per unit gross domestic product) by 67% from 1980 to 2010, it is now the world's largest energy consumer and biggest emitter of carbon dioxide (CO_2), the chief greenhouse gas (GHG) [1]. Hence, China is facing immense energy related pressures and challenges, such as energy supply shortage, high foreign dependency for oil, massive acid deposition, and growing international pressure about GHG emissions reduction [2, 3].

The adequate supply of infrastructure services has long been recognized as an essential ingredient for productivity improvement and economic growth [4, 5]. For China, there is persuasive evidence that sufficient infrastructure provision is a key element to achieve its intended objective of export growth [6]. Also, increasing access to infrastructure services in China has played a key role in helping reduce income inequality and increase efficient resource reallocation [7]. China has undergone a remarkable economic growth with an annual growth rate over 10% from 1980 to 2010, which is mainly driven by sustained increase in domestic investment and a massive development of physical infrastructure [8, 9]. However, infrastructure investment will not only bring a large amount of energy consumption directly and will also result in energy consumption indirectly through the use of cement, iron, steel, and other energy-intensive products. The role of infrastructure investment played on energy use has received increased attentions.

Either the input-output model or life-cycle assessment model could be established to quantitatively evaluate the impacts of infrastructure construction on energy use. But the application of Life-Cycle Assessment has been limited by data availability in practice [2, 3, 10]. Input-output analysis is a useful analytical framework developed by Leontief [11]. It uses input-output table to estimate the direct and indirect impacts of one economic sector's output changes on other sectors [12–14]. Therefore it can conveniently evaluate the quantitative relationships among all economic sectors, including the energy producers and its users [15–17].

In recent years, input-output analysis has been widely applied in evaluating the energy consumption caused by

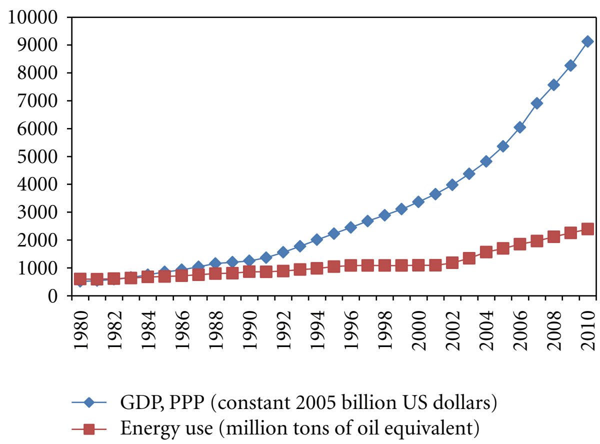

FIGURE 1: China's energy use and GDP from 1980 to 2010.

different economic activities in national or regional economies [18, 19]. Pick and Becker [20] applied input-output analysis to evaluate direct and indirect uses of energy and materials in engineering and construction. Nässén et al. [21] use top-down input-output analysis to assess direct and indirect energy use as well as carbon emissions in the Swedish building sector and compared the results to that from 18 previous bottom-up studies using process-LCA methodology. For China's case, many scholars have already studied the impacts of different economic activities on energy consumption. Polenske and McMichael [22] use input-output analysis to analyse the energy consumption and environmental pollution in China's coke-making industry. Liu et al. [16] comprehensively evaluated households' indirect energy consumption and impacts of alternative energy policies in China. Liange et al. [23] propose a hybrid physical input-output model to study energy metabolism by taking Suzhou in China as an example.

However, few analysts have studied the infrastructure investment impacts on energy consumption. In this paper, we measure the energy use embodied in China's infrastructure investment, which aims to provide critical insights for the country's policy-makers to refine the current intensity-reduction-oriented energy-efficiency policies. We first build an energy input-output model to identify quantitatively the amounts of China's energy use embodied in infrastructure in 1992, 1997, 2002, and 2007. We also use the model to analyze the key factors driving the growth of energy use embodied in infrastructure for the same period.

2. Energy Input-Output Analysis

Infrastructure could be defined as the basic physical systems needed for one country or one region's economy to function, including transportation, water, sewage, communication, and electric systems. According to national economic accounting, infrastructure investment is a part of GDP measured from the expenditure side [24]. Infrastructure investment plays an important role in expanding China's economic growth by providing increasing production conditions of various economic sectors. Like other economic activities, infrastructure investment consumes both energy and nonenergy goods and services, so that the energy consumed by infrastructure investment should take the embodied energy of all these goods and services into account.

2.1. Energy Input-Output Model. Beginning from the basic Leontief Input-output model, the total output of an economy, $\mathbf{X}$, can be expressed as the sum of intermediate consumption, $\mathbf{AX}$, and final consumption, $\mathbf{Y}$ [11]:

$$\mathbf{X} = \mathbf{AX} + \mathbf{Y}, \qquad (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{B}, \tag{1}$$

where $\mathbf{X}$ is the $n \times 1$ total output vector, $\mathbf{A}$ is the $n \times n$ direct input coefficient matrix, describing the interindustry relationships between all sectors of the economy, $\mathbf{Y}$ is the $n\times 1$ final demand vector, and $\mathbf{B}$ is the Leontief inverse matrix, $(\mathbf{I} - \mathbf{A})^{-1}$. $\mathbf{AX}$ denotes the intermediate input vector, which can be obtained by multiplying the direct input coefficient matrix by the total output vector. The final demand vector, $\mathbf{Y}$, can be treated as exogenous to the system; for example, the level of total production can be determined by the final demand (2):

$$\mathbf{Y} = \mathbf{BX}. \tag{2}$$

Input-output model can be applied to calculate each sector's indirect energy consumption regardless of the length and complexity of their production processes by using the energy input-output table (Wu and Chen, 1990; Peet, 1993). In energy input-output tables, energy sectors should be represented both in monetary and energy terms for computing the direct energy consumption coefficient matrix [14]. Assume that in input-output tables the economy can be categorized into n sectors, which includes k energy sectors and n-k nonenergy sectors. Hence we can write an equation representing the way in which energy sectors distribute their products to energy sectors, nonenergy sectors, and final demands in physic units:

$$A_{k,1} + A_{k,2} + \cdots + A_{k,k} + A_{k,k+1} + \cdots A_{k,n} + f_k = x_k. \tag{3}$$

Using energy input-output tables, the direct energy intensity and total energy intensity of each economic sector can be calculated. Direct energy intensity of one sector is calculated as the ratio of direct energy consumption (in physical terms) to total inputs (in monetary terms). Total energy intensities are calculated by multiplying direct energy intensity matrix with the Leontief inverse matrix of the corresponding energy input-output table. Embodied energy use in infrastructure investment can be calculated by multiplying total energy intensities with infrastructure investment:

$$e_i = \frac{\sum_{i=1}^{k} E_{j,1}}{X_i}, \tag{4}$$

$$\mathbf{e}^{\mathbf{total}} = \mathbf{e}(\mathbf{I} - \mathbf{A})^{-1}, \tag{5}$$

$$\mathbf{E}^{\mathbf{II}} = \mathbf{e}^{\mathbf{total}}\mathbf{Y}^{\mathbf{II}} = \mathbf{e}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}^{\mathbf{II}}. \tag{6}$$

e_i is the direct energy intensity of sector i, $\mathbf{e}$ is the direct energy intensity matrix,and $\mathbf{e}^{\mathbf{total}}$ is the total energy intensity matrix. $\mathbf{E}^{\mathbf{II}}$ is the embodied energy in infrastructure investment, and $\mathbf{Y}^{\mathbf{II}}$ is the infrastructure investment.

2.2. Structural Decomposition Analysis. Based on (6), the change of embodied energy use in infrastructure investment is driven by several factors, such as growth in infrastructure investment, energy efficiency improvement, and industrial structure changes. Aiming at identifying the driving factors for changes in embodied energy use in infrastructure investment overtime, we applied input-output structural decomposition analysis on (6). Beginning from the basic Leontief model, change in the embodied energy use in infrastructure investment can be expressed as follows:

$$\Delta E^{II} = \mathbf{e}_{\mathbf{t}}(\mathbf{I} - \mathbf{A}_{\mathbf{t}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t}} - \mathbf{e}_{\mathbf{t-1}}(\mathbf{I} - \mathbf{A}_{\mathbf{t-1}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t-1}}, \quad (7)$$

where $\Delta E^{II} = E^{II}_t - E^{II}_{t-1}$, and ΔE^{II} is the change of embodied energy use in infrastructure investment during the period $[t-1, t]$.

Equation (7) can be decomposed to analyze changes in embodied energy use in infrastructure investment over time. We use a common decomposition method to separate factors related ((8a), which represents aggregated changes in the direct energy intensities), the Leontief effect ((8b), which is change in intersector relationships), and infrastructure investment ((8c) which represents changes in infrastructure investment) [25–27].

$$\begin{aligned}
\text{Equation (7)} = {} & \mathbf{e}_{\mathbf{t}}(\mathbf{I} - \mathbf{A}_{\mathbf{t-1}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t-1}} - \mathbf{e}_{\mathbf{t-1}}(\mathbf{I} - \mathbf{A}_{\mathbf{t-1}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t-1}} && \text{(8a)}\\
& + \mathbf{e}_{\mathbf{t-1}}(\mathbf{I} - \mathbf{A}_{\mathbf{t}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t-1}} - \mathbf{e}_{\mathbf{t-1}}(\mathbf{I} - \mathbf{A}_{\mathbf{t-1}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t-1}} && \text{(8b)}\\
& + \mathbf{e}_{\mathbf{t-1}}(\mathbf{I} - \mathbf{A}_{\mathbf{t-1}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t}} - \mathbf{e}_{\mathbf{t-1}}(\mathbf{I} - \mathbf{A}_{\mathbf{t-1}})^{-1}\mathbf{Y}^{\mathbf{II}}_{\mathbf{t-1}} && \text{(8c)}\\
& + \varepsilon. && \text{(8d)}
\end{aligned}$$

2.3. Data Input. This paper aims to analyse the embodied energy use in physical infrastructure investment, including investment in transport services, communication, energy supply, and water management. In order to carry out a detailed analysis of the impact of physical infrastructure investment, there is a need to disaggregate investment by sector. The datasets that will be used in our study are input-output tables, the Income and Expenditure Survey, and Investment Survey from the National Bureau of Statistics of China.

Given the energy input-output model, we constructed hybrid unit energy input-output tables [14] based on monetary input-output tables published by the National Bureau of Statistics of China from 1992 to 2007. In hybrid unit energy input-output tables, the energy sectors' products are presented both in physical units (e.g., tonnes of coal equivalent) and monetary terms, and the nonenergy sectors' products are presented only in monetary terms. The data of energy sectors' products are extracted from Chinese Energy Statistical Year books. To calibrate the data of the input-output tables and energy statistics, we adjust the sector classification of the input-output tables. For more details about data calibration of hybrid unit energy input-output tables, refer to [28].

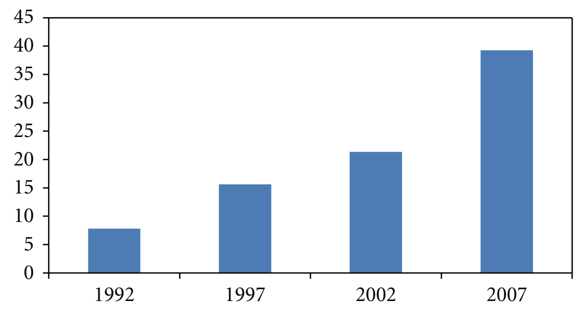

Figure 2: China's embodied energy use in infrastructure investment in absolute term (million tons of standard coal).

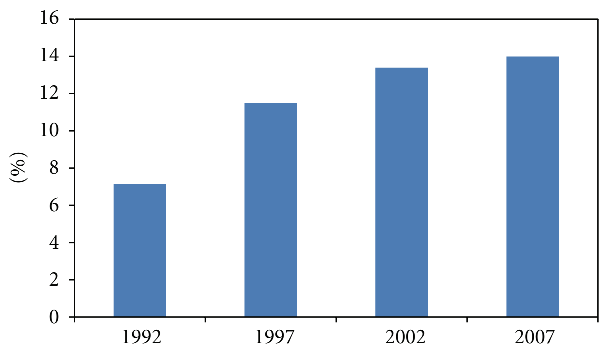

Figure 3: China's embodied energy use in infrastructure investment in percentage of its total energy use.

3. Results and Discussion

3.1. Results. The overall results of China's embodied energy use in infrastructure investment are reported in Figures 2 and 3, in absolute term and percentage of China's total energy use, respectively. China's fast-increasing infrastructure investment, with annual growth rate 25% from 1992 to 2007, has led to accelerated requirements of energy. As shown in Figure 2, China's embodied energy use in infrastructure investment increased from 78 million tons of standard coal in 1992 to 354 tons of standard coal in 2007. The results also show that the embodied energy use in infrastructure investment has increased rapidly from 2002 to 2007. The embodied energy use in infrastructure investment growth from 2002 to 2007 was about 140 million tons of standard coal, which is more than the growth of embodied energy use in infrastructure investment from 1992 to 2002.

In terms of proportion, the embodied energy use in infrastructure investment accounted for 7.16% of China's total energy use in 1992, and the proportion increased to 13.4% in 2002. Then it increased to 14.0% in 2007, which means that it has accounted for a significant proportion of China's total energy use during our observation period and it is one of the key factors driving China's energy consumption growth. From 1992 to 2007, China's total energy

Table 1: The structural decomposition results of China's embodied energy use in infrastructure investment.

	1992–1997	1997–2002	2002–2007
ΔI_{ei}	−64.90	−34.85	−58.01
ΔI_{is}	−6.26	−1.20	−2.33
ΔI_{ii}	149.35	93.17	239.40
ΔI_{eII}	78.19	57.13	179.06

(a) Negative values indicate effects of decreasing embodied energy use in infrastructure investment.
(b) $\Delta I_{ei}, \Delta I_{is}, \Delta I_{ii}$ and ΔI_{eII} are the effect of direct energy intensities, the industrial structure effect, changes in infrastructure investment and change in embodied energy use in infrastructure investment respectively.

use increased from 1.10 billion tons of standard coal to 2.81 billion tons of standard coal. Hence, the infrastructure investment could play an important role in inducing China's energy consumption as well as GHG emissions.

The structural decomposition results of China's embodied energy use in infrastructure investment are shown in Table 1. Energy efficiency improvement in China, indicated as decreasing in energy intensities, is the main factor to hinder the growth of embodied energy use in infrastructure investment. Changes of industrial structure also have decreased China's embodied energy use in infrastructure investment while the growth of China's infrastructure investment, which was the most significant impact factor, led to the increase of embodied energy use in infrastructure investment. Infrastructure investment activities, mainly occurred in the construction sector, usually consume a huge amount of energy-intensive materials, such as cement and steel, which causes significant indirect energy consumption from a life-cycle perspective. Therefore, these results indicate that in order to reduce the embodied energy use in infrastructure investment, it is important to decrease the energy use embodied in these energy-intensive materials, prolong the lifespan of infrastructure, and improve the design of infrastructure investment policies.

3.2. Discussion. Generally, infrastructure investment is considered to have significant positive multiplier (generative) effects on national economy, because it could not only improve the productivity, but also trigger investment from other economic sectors and ultimately increase national income. In recent years, for railway projects only, more than 4 trillion Yuan ($597 billion, 1 US dollar = 6.6 Yuan as in 2010) has been approved in China, and a large proportion of which targeted the high-speed rail lines (Ministry of Railways 2010). Except for the economic benefits associated with high-speed rail investment, high-speed rail is also considered as energy efficient and environment friendly since it is electrified and does not generate carbon emissions during operation.

However, the claimed benefits associated with infrastructure investment, which are related to economic development or climate change mitigation goals, still need close inspection as well as quantitative research efforts. Take high-speed rail as an example; even though the direct energy use of high-speed rail is clean during the operation period, its direct energy consumption during the construction period is enormous, regarding the production and shipment of major building materials, that is, cement and steel. Moreover, it is true that high-speed rail is mostly electrified, but the supply of power is not necessarily low-carbon. In the case of China, because over 80% of the electricity is currently generated from coal, it is highly possible that, the reduction of energy intensity and carbon emissions along the high-speed rail corridor is at the cost of intensified energy use in regions where power plants locate. Finally, if in fact there are not enough passengers traveling on the high-speed rail line, the per capita energy consumption and carbon emissions could rise rapidly.

Infrastructure projects incur huge amounts of upfront costs, but the environmental influences go beyond the project life cycle. The standard cost-benefit analysis framework used by China's development authorities could not captured these influences. A comprehensive and systematic assessment of energy use impacts of infrastructure investment is essential to understand the role of infrastructure investment in achieving the goals of climate change mitigation. For China, the central government should be aware of the temporary nature of the stimulus effects of infrastructure investment, even though the short-run impacts may be significant in magnitude. Because in the long run marginal returns to infrastructure improvement are decreasing and the direct and indirect energy use of infrastructure is huge. The government needs to seek for more sustainable driving forces of economic development and needs to be aware of the risk of overbuilding.

4. Conclusion

This paper aims at improve the understanding of the implications of China's infrastructure investment on its energy use. Based on the energy input-output analysis, we calculated the embodied energy use in infrastructure investment from 1992 to 2007. We also quantitatively analyzed the factors impacting the embodied energy use in infrastructure investment using a structure decomposition analysis. The results obtained from the energy input-output analysis show that an increasing trend of both China's energy embodied in infrastructure investment as well as the ratio of China's energy embodied in infrastructure investment to its total energy consumption during our observation period. The decomposition results show that energy efficiency improvement is the main reason for hindering the growth of energy embodied in infrastructure investment and the increase of infrastructure investment is the most important factor driving the growth of energy embodied in infrastructure investment.

Our results reflect that the infrastructure growth required by China's rapid urbanization and industrialization has consumed a large amount of energy. Given this fact, we can conclude that the problems of repetitive layout, improper location, mutual contradiction, and bad structure existing in China's infrastructure represent inefficient use of capital, energy, and other resources consumed by corresponding infrastructure investment activities. Chinese policy makers should improve their design of the country's infrastructure investment policies in terms of further determining the energy-saving potentials of China's economy from the perspective which we presented through this study.

Acknowledgments

The authors are grateful to the Chinese Academy of Sciences for their data and would like to thank the referee for his/her helpful comments.

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The Scientific World Journal
Volume 2012, Article ID 909317, 5 pages
doi:10.1100/2012/909317

The ScientificWorldJOURNAL

Research Article

Evaluating Ecological and Economic Benefits of a Low-Carbon Industrial Park Based on Millennium Ecosystem Assessment Framework

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Received 7 November 2012; Accepted 4 December 2012

Academic Editors: V. Calderón and A. L. Mayer

The Millennium Ecosystem Assessment (MA) framework was modified with a special focus on ecosystem service values. A case study of a typical low-carbon industrial park in Beijing was conducted to assess the ecological and economic benefits. The total economic value of this industrial park per year is estimated to be 1.37×10^8 RMB yuan, where the accommodating and social cultural services are the largest two contributors. Due to the construction of small grasslands or green roofs, considerable environmental regulation services are also provided by the park. However, compared with an ecoindustrial park, carbon mitigation is the most prominent service for the low-carbon industrial park. It can be concluded that low-carbon industrial park construction is an efficacious way to achieve coordinated development of society, economy, and environment, and a promising approach to achieving energy saving and carbon reduction.

1. Introduction

The services of ecological systems and the natural capital stocks are critical to the functioning of the Earth's life-support system. They contribute to human welfare, both directly and indirectly, and thereby represent a part of the total economic value of the planet [1]. However, these services are not fully recognized by human societies. The economic evaluation of ecosystem services is becoming an effective way to understand the multiple benefits provided by ecosystem services. Assessing the economic values of ecosystem services is thus an effective way to link human activities and natural systems [2]. As a specific interdisciplinary field of practice, ecosystem service evaluation has been conducted by many researchers. Daily provided a detailed compendium on describing, measuring, and valuing ecosystem services [3]. Costanza performed a monetary study to value the world's ecosystem service and natural capital [1] and further, conducted a multi-scale study to assess biodiversity and ecosystem service [4]. Hougner et al. investigated the economic valuation of a seed dispersal service in the Stockholm National Urban Park by taking into account biodiversity values [5]. Sattout et al. applied contingent valuation method to assess the economic value of cedar relics [6]. Spash et al. discussed the motives behind willingness to pay for biodiversity improvement in a water ecosystem [7]. However, these existing studies are still focused on estimating the value of natural ecosystem services with few studies valuing the artificial ecosystem services.

Artificial ecosystem services are similar to natural ecosystem services in essence, but differ in the following main aspects: (1) enhancement of certain services and decline of most other services in artificial ecosystems compared to natural ecosystems [8]; (2) higher direct use values than indirect use values are usually estimated through artificial ecosystem services in comparison with natural ecosystem services. Efforts have been made to estimate the ecosystem services of artificial systems, for example, Tian and Cai evaluated the ecosystem services of artificial landscapes in Beijing [9], and Shen et al. assessed the environmental and economic values for constructed wetlands [10].

Industrial park is a typical artificial ecosystem and functions as a small "city" with complete infrastructural facilities, internal material and information flows, and semi-artificial environmental conditions. As a new kind of industrial agglomeration mode, low-carbon industrial parks have recently been playing a key role in achieving global carbon emission mitigation and promoting a low-carbon economy. Low-carbon industrial park can be defined as a well-operated cluster of firms and organizations designed to maximize its social economic output and minimize its greenhouse gas (GHG) emissions. The implication of low-carbon parks does not only lie in energy conservation and emission reduction, but also a new mode featuring the integration of green, ecological and sustainable development, that is, practicing low-carbon ecological designs so as to realize the harmony between human society and nature.

The construction of low-carbon industrial parks can reduce GHG emissions and environmental pollution caused by energy consumption, thereby bringing in huge ecosystem service values. To quantify the ecosystem service provided by low-carbon industrial parks, the Millennium Ecosystem Assessment (MA) framework is employed in this paper. MA was initiated in 2001 with the objective to assess the consequences of ecosystem change for human well-being, which provided the scientific basis for actions needed to enhance the conservation and sustainable use of those systems. The involved works in the MA framework provide a state-of-the-art scientific appraisal of the condition and trends in the world's ecosystems and the services they provide (such as clean water, food, forest products, flood control, and natural resources) and the options to restore, conserve, or enhance the sustainable use of ecosystems.

In this study, we proposed an ecosystem service evaluation framework based on MA to assess the ecological and economic value of low-carbon industrial parks. Section 2 demonstrates the ecosystem services quantitation method. In Section 3, a case of a low-carbon industrial park in Beijing is introduced, and the results of ecosystem services evaluation are integrated and demonstrated. Finally, Section 4 presents the conclusions of this study.

2. Methodology

Potential ecosystem services brought by the low-carbon industrial parks are categorized into accommodating benefit, GHG emission reduction benefit, environmental benefit, and social benefit. Accommodating benefit results from the provision of workplace for the settled enterprises. GHG emission reduction benefit comes from the utilization of carbon-reducing building materials in the construction stage and application of renewable energy in the operation stage. Environmental benefit is derived from two approaches, that is, the utilization of renewable energy, which is beneficial in protecting forest resource and decreasing the traditional fossil energy consumption, and the green land project in the low-carbon industrial park. Social benefit is attributable to the provision of job opportunity.

In the MA framework, ecosystem services are divided into four parts, that is, supporting services, regulation services, provisioning services, and cultural services [2]. As most of these services can be provided by the low-carbon industrial park, the MA framework is appropriate to quantify these benefits in the form of monetary value. In this study, the ecosystem services of the MA framework are thereby quantified as four categories, that is, accommodating service value, GHG emission reduction value, environmental regulation value, and social cultural service value (Figure 1).

2.1. Accommodating Service Values. Low-carbon industrial park has accommodated many establishments and provided them with workspaces, so it generates a housing value (HV), which can be estimated by

$$\mathrm{HV} = P_H \times \frac{A_H}{T_H}, \tag{1}$$

where HV is the living value. P_H is the average selling price of buildings in the industrial park. A_H is the sales area. T_H is the years that land can be used by the industrial park.

2.2. GHG Emission Reduction Values (GV). Comparing the carbon emissions of the concerned low-carbon industrial park with other traditional industrial parks, the carbon benefits of the low-carbon industrial park can be obtained. Combined with economic methods such as replacement cost or shadow price, the GHG emission reduction service value is calculated based on the price element in the Carbon Market Europe:

$$\mathrm{GV} = P_C \times Q_C, \tag{2}$$

where GV is GHG emission reduction value, P_C is the price of carbon in the CER Carbon Market Europe [11], and Q_C is the carbon emission reductions, in unit of tCO_2 equivalent.

2.3. Environmental Regulation Values (ERV). Based on the example of European Union's research about ecological economic values of small grasslands or green roof [12], the replacement cost method [13, 14] is employed to calculate the ecosystem services values of grassland and plants in low-carbon industrial parks.

2.3.1. Carbon Fixation and Oxygen Supply Values (CV and OV). CV can be estimated based on the photosynthesis equations and the shadow price of forestry restoration cost (20 dollars/t) [15]. The equation is shown as follows:

$$\mathrm{CV} = T_C \times Q_{\mathrm{CO_2}} \times 0.27, \tag{3}$$

where CV is carbon fixation value, T_C is the shadow price of forestry restoration cost, $Q_{\mathrm{CO_2}}$ is the amount of CO_2 fixation, and 0.27 is the carbon content coefficient of CO_2 emission.

OV can be estimated by replacement cost method based on the Net Primary Productivity (NPP) and the cost of

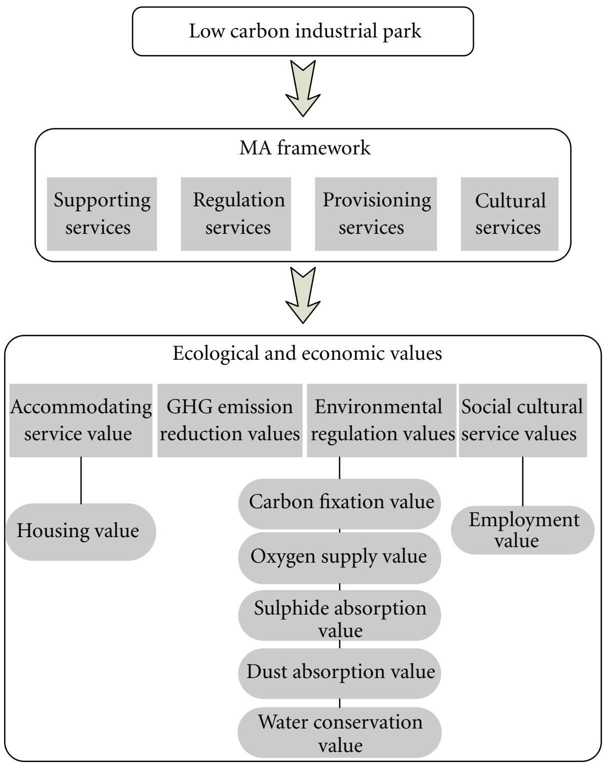

Figure 1: Ecological and economic value assessment framework of the low-carbon industrial parks.

industrial oxygen production [15]. The equation is demonstrated below

$$\mathrm{OV} = C_{\mathrm{O_2}} \times \mathrm{NPP} \times 1.2, \quad (4)$$

where OV is the oxygen supply value, $C_{\mathrm{O_2}}$ is the cost of industrial oxygen production, NPP is the net primary productivity of plants, and 1.2 is oxygen release ratio per biomass production that is determined by the photosynthesis equation.

2.3.2. Air Purification Values. In this study, the purification services of ecosystem mainly include the absorption of sulphide and dust [16], which are calculated as follows:

$$\mathrm{SV} = C_S \times Q_{\mathrm{SO_2}}, \qquad \mathrm{DV} = C_D \times Q_D, \quad (5)$$

where SV is the sulphide absorption value, C_S is the per unit SO_2 reduction cost, derived from the average investment on SO_2 treatment per unit SO_2 reduction according the environmental statistics [17], and $Q_{\mathrm{SO_2}}$ is the amount of SO_2 absorption; DV is dust absorption value, C_D is the cost of industrial de-dusting, and Q_D is the amount of dust absorption [15].

2.3.3. Water Conservation Values (WV). Water area in low-carbon industrial park provides the water conservation services, which can be estimated by shadow price approach using reservoir storage cost in China (0.67 RMB/m^3) [16]. The equation is shown as follows:

$$\mathrm{WV} = C_W \times Q_W, \quad (6)$$

where WV is water conservation value, C_W is the per unit reservoir storage cost in China, and Q_W is the amount of water conservation in the industrial park.

Finally, environmental regulation values can be described as

$$\mathrm{ERV} = \mathrm{CV} + \mathrm{OV} + \mathrm{SV} + \mathrm{DV} + \mathrm{WV}. \quad (7)$$

2.4. Social Cultural Service Values (SCV). Low-carbon industrial park can provide multiple social cultural services, such as scientific research, production, landscape appreciation, and entertainment. Only the employment value is considered in this study due to data availability.

The low-carbon industrial park provides various employment opportunities, so the employment value can be estimated as follows:

$$\mathrm{EV} = W_3 \times F_3, \quad (8)$$

where EV is employment value, W_3 is the average wage per capita in tertiary industry, and F_3 is the amount of employment in tertiary industry.

3. Case Study

The concerned low-carbon industrial park is located in the northeast of Daxing District in Beijing. The industrial park has a floor space of 0.174 million square meters and built up area of 0.336 million square meters. Totally 43 buildings are distributed in this industrial park with high-end industries like intelligent, innovative, and design enterprises. So far, this industrial park has accommodated 49 enterprises with employment surpassing 2000 people.

The park covers a green area of 41,839 square meters and a water area of 5,073 square meters, of which the floor area ratio is 0.77 and the greening ratio is 41%. It emits only 0.7 ton CO_2 equivalent per 10,000 GDP, which is less than 1/4 of that of the industrial output in China and 1/2 of that of the tertiary industrial [18]. A rainwater collection system and a waste water treatment system are also installed as auxiliary engineering to achieve water recycling and reuse.

Data for the low-carbon industrial park are provided by Beijing Development Area [18] including the total GHG emission per year, economic and environmental data, and information of settled enterprises. Some of the parameters are summarized and listed in Table 1.

We estimated each type of value in the low-carbon industrial park per year. The total ecological and economic value of the low-carbon industrial park is 1.37×10^8 RMB yuan/a. It consists of accommodating service value, GV, ERV, and SCV, which are 1.13×10^7, 1.07×10^6, 2.31×10^6, and 1.22×10^8 RMB yuan/a, respectively. Specific values of each service are shown in Table 1.

As shown in Table 2, we can see that the employment value (EV) accounts for the largest proportion of the total

Table 1: Main parameters of the low carbon industrial park.

Parameters	Value	Parameters	Value
Floor area	$1.74E+05\ m^2$	Greening area	$4.18E+04\ m^2$
Employment	2000	Water recycling rate	50.80%
Operation years	48 years	Registered capital	$1.31E+10$ yuan
GHG emission intensity	0.07 tCO_2 eq/yuan	GHG emission avoided	0.24 tCO_2 eq/yuan

Table 2: The economic value of each ecological service.

Type	Service	Value (RMB yuan/a)
Accommodating service values	Housing value (HV)	1.13×10^7
GHG emission reduction values (GV)	GHG emission reduction	1.07×10^6
Environmental regulation values (ERV)	Carbon fixation (CV)	7.20×10^5
	Oxygen supply (OV)	1.05×10^6
	Sulfide absorption (SV)	2.10×10^4
	Dust absorption (DV)	4.80×10^5
	Water conservation (WV)	3.40×10^4
Social cultural service values	Employment value (EV)	1.22×10^8
Total values (SCV)		1.37×10^8

values with a percentage of nearly 89%. This is generally due to the type of companies in the industrial park, most of which belong to the tertiary industry with a much higher average salary level. Housing value also represents a large portion of the total value with a ratio of 8.24%. As the prices of house keep soaring, even residents with a national average salary cannot afford a house in Beijing, implying that the housing value of buildings is far more than its real value. These two values are the direct values that we can find in the market. However, the most precious values of low-carbon industrial park are environmental and ecological values that cannot be evaluated by market prices. Thus, a specific analysis of GV and ERV is made in the following part. The results are shown in Figure 2.

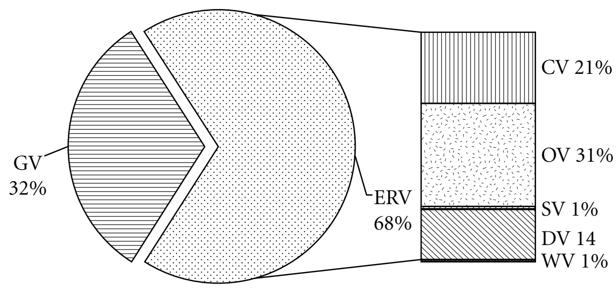

Figure 2: The proportion of CV and ERV of the low-carbon industrial park.

The total GV and ERV of the park is 3.38×10^6 RMB yuan/a, which implies that 3.38×10^6 RMB yuan more ecological benefits per year are gained in the park compared with traditional industrial park due to the utilization of renewable energy and green land construction. As shown in Figure 2, ERV constitutes the largest proportion of 68%, followed by the GV (32%).

The constitutions of the ecological services are further decomposed in Figure 2. Among ERVs, the CV and OV make up the largest proportion. The DV also accounts for a significant portion of 14%. The SV value and WV only make up a relatively small fraction, indicating that the effects of low-carbon industrial park in SO_2 emission reduction and water conservation are not prominent.

It can be seen that GV is only half of ERV, implying that low-carbon industrial parks are also a kind of ecoindustrial parks with emphasis on energy saving and emission reduction.

The comparisons of this low-carbon industrial park and an ecoindustrial park [19] are demonstrated in Figure 3. The indicator of ecosystem service per area is used as a numéraire for the assessment. Obviously, the GV of the park is 1.77 times of that of the ecoindustrial park. However, the ERV of the ecoindustrial park (10.81) is a little higher than that of the low-carbon industrial park (6.86). Thus, we can conclude that the advantage of low-carbon industrial parks is carbon mitigation, rather than ecological construction, which is the theme of an ecoindustrial park.

4. Conclusions

The total value of a low-carbon industrial park in Beijing is calculated to be 1.37×10^8 RMB yuan/a. The results show that the low-carbon mode can bring the industrial parks tremendous ecological, social, and GHG benefits, especially in terms of ecosystem service and GHG emission reduction. This case is thus a benchmark for future industrial park construction in the context of low-carbon development. In addition, except for GHG emission, low-carbon industrial parks are of significant ecological importance. Therefore, the low-carbon industrial park is not only an effective measure to solve the contradiction between high-speed development

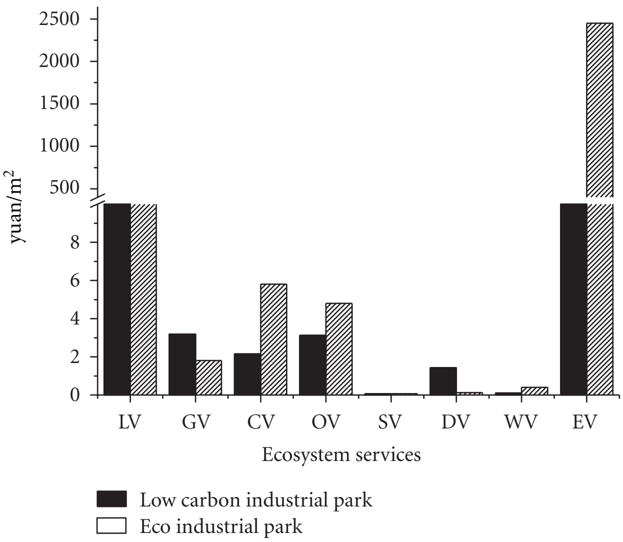

Figure 3: Comparison of the low-carbon industrial park with an ecoindustrial park.

and high emission in the economic society of industrial park, but also an efficacious way to achieve society-economy-ecology sustainable development.

Acknowledgments

This study was supported by Fund for Creative Research Groups of the National Natural Science Foundation of China, (Grant no. 51121003), Key Program of National Natural Science Foundation (nos. 50939001 and 41271543), and Program for New Century Excellent Talents in University (NCET-09-0226). The authors are especially grateful for the financial support from Beijing Development Area Co., Ltd.

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The Scientific World Journal
Volume 2012, Article ID 305474, 9 pages
doi:10.1100/2012/305474

The ScientificWorldJOURNAL

Research Article

Ecological Network Analysis for a Low-Carbon and High-Tech Industrial Park

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Received 7 September 2012; Accepted 8 November 2012

Academic Editors: V. Kazukauskas, R. Maceiras, S. S. Martinez, S. Medved, and J. L. Míguez

Industrial sector is one of the indispensable contributors in global warming. Even if the occurrence of ecoindustrial parks (EIPs) seems to be a good improvement in saving ecological crises, there is still a lack of definitional clarity and in-depth researches on low-carbon industrial parks. In order to reveal the processes of carbon metabolism in a low-carbon high-tech industrial park, we selected Beijing Development Area (BDA) International Business Park in Beijing, China as case study, establishing a seven-compartment- model low-carbon metabolic network based on the methodology of Ecological Network Analysis (ENA). Integrating the Network Utility Analysis (NUA), Network Control Analysis (NCA), and system-wide indicators, we compartmentalized system sectors into ecological structure and analyzed dependence and control degree based on carbon metabolism. The results suggest that indirect flows reveal more mutuality and exploitation relation between system compartments and they are prone to positive sides for the stability of the whole system. The ecological structure develops well as an approximate pyramidal structure, and the carbon metabolism of BDA proves self-mutualistic and sustainable. Construction and waste management were found to be two active sectors impacting carbon metabolism, which was mainly regulated by internal and external environment.

1. Introduction

The study of ecoindustrial parks (EIPs) has assumed great deal of importance within the past ten to fifteen years. One of the best definitions of an EIP has been provided by the UESPA, which was stated as "*a community of manufacturing and service businesses seeking enhanced environmental and economic performance by collaborating in the management of environmental and reuse issues. By working together the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only*" [1]. This definition mainly aims to close material cycles in the industrial chain and considers the entire life cycle from raw material production to product consumption and waste management [2].

Despite cooperation between companies to find win-win solutions [3], from the traditional perspective of EIPs, one of their strong points is basically focused on the structural planning and functional utility of industrial recycling. It means that a better design or running of EIPs' cycle have arisen to reduce waste management and disposal costs, extract with cheaper materials and energy, and gain benefits from residues [4]. However, in the more furious conflict between development of economic society and recovery of polluted ecosystem, grimmer situation and stricter requirements will be put forward. Traditional definition of EIPs cannot adapt to the social development better, especially when the whole world is paying more attention on climate change.

Climate change announces a fast global socioeconomic transition, but nobody could predict the ultimate results of the next industrial revolution. Obviously, business and government play a key role in promoting or destroying the revolution. It is undeniable that climate change affects both natural ecosystems and human societies [5–7]. Taking climate change into consideration, EIPs can be classified into green industry parks and integrated ecoindustry parks. Therein, green industry park was defined as "*a range of enterprises that use cleaner production technologies, process much of their waste and/or reduce the emissions of greenhouse gases, in situ*" [8]. In Belgium, green industry park is embodied as the "carbon neutral industrial parks," an initiative of the Flemish region, which brings in the carbon footprint of companies into the quality requirements for industrial parks to enforce carbon emission reduction and sustainable energy policy measures [7]. And some studies have suggested that it is practical to implement climate change through industrial symbiosis [9, 10] and energy innovation in EIPs [11].

An industrial ecosystem is constructed with the flows of matter, nutrients, energy, and carbon [12]. As a necessary part of industrial flows, some scientists make great contribution to stretch out the carbon cycle in different industrial ecosystem. Korhonen et al. considered the material (including carbon flow) and energy flows of forest ecosystem in Finland [12]. Liu et al. provided an outline of energy-based greenhouse gas emissions inventory in Suzhou Industrial Park, China [13]. Norstebo et al. and Midthun et al. both analyzed the taxation of CO_2 emissions and carbon capture in a case study of an extension of an EIP in Norway [14, 15]. Munir et al. presented a newly developed carbon emission Pinch Analysis technique for achieving holistic minimum carbon targets in EIPs [16]. Besides, there is still a lack of speciality of the system-wide carbon emission in an EIP.

EIPs originate from three major concepts, namely, scilicet industrial ecology, biological ecology, and the spatial perspectives based on landscape ecology [17]. In the second field of EIPs, scientists have tried to seek the inner-mimicry from biological individuals with industrial unit to natural ecosystem with industrial system. It is a metaphor running through the biological-industrial process, structure, and function. Hence the concept of industrial metabolism is first established by Ayres, which is defined as "*the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes*" [18, 19]. The summary of industrial metabolism is analyzing the whole material flows, extracting all possible emission sources, and assessing the influences within these flows [20]. After that, Graedel shows a good example in using statistical indexes of food web from natural ecosystems for reference in his evaluations of EIPs [21].

Nowadays, diverse analysis tools are used in the research of EIPs, which can be classified into two main trends of methodology. One of them is generally based on the inventorying of life-cycle ecological and economic input-output flows, including material flow analysis [3, 22], input-output analysis [23], life-cycle assessment [24], and structure and network analysis based on industrial metabolism [20, 25, 26]. The other method is concerned with the idea of the available solar energy.

Ecological Network Analysis (ENA) is a general metabolism-based analytical tool for studying the system connectivity and for quantifying and qualifying direct and indirect ecological flows in the system [27]. In general, the key concepts of ENA are behavior, structure, and function of a system [27]. An EIP can be extracted as a symbiotic network, where many material and energy flows link diverse compartments in ensuring a smooth running of industrial processes (both of the components' mutual interactions in integral environment and the passing relationship between integral and external environment) and system functioning. So it is appropriate to introduce ENA into EIP study. However, present attempts in seeking carbon metabolism in EIPs based on the network view are still a blank space, and challenges include defining what low-carbon high-tech industrial park is (especially in what "low-carbon" could be defined), understanding why these parks could reduce more carbon emission, as well as seeking to use an accessible tool for metabolic structure and functioning study. The adoption of ENA may provide a feasible prospect in resolving the latter two issues by evaluating the metabolic intensities, processes, structure, and control of carbon emissions.

In China, there exists a conflict among economic development, shortage of natural resource, and serious pollution suggested by the impetus for developing EIPs [28]. Hence developing high-tech industrial parks has been a promising trend of EIPs' development. These EIPs generally assemble high-tech business located in the upstream of industrial chain, such as companies in the domains of intellective, R & D, design, or head office. BDA International Business Park (BDA) is situated in Beijing High-Tech Industrial Park, which is characterized as its graceful ecological environment, low energy consumption, low carbon emission intensity, and amassing of high-tech business. As a feasible trial in developing low-carbon industrial parks, BDA covers a landscape area of $0.1735\,km^2$ and a construction area of $0.336\,km^2$. The park consists of 34 separate office buildings where 159 high-tech companies have been stationed in total. It is worth emphasizing that BDA is the first EIP considering the low-carbonic concept in its design in Beijing. This study tries to present an ENA-based methodology for carbon metabolism in low-carbon high-tech industrial parks and selects BDA as a case study for promoting carbon reduction in EIPs.

2. Materials and Methods

2.1. Ecological Network Model for Low-Carbon High-Tech Industrial Park. The essence of ecological network model is a transmitting network for materials and energy, which includes both of the components' mutual interactions in integral environment and the passing relationship between integral and external environment. For this sake, establishing the reasonable system boundary and making sure of limiting factors should be the necessary step for the ecological network model.

Even though EIPs are mainly artificially controlled, both artificial and natural processes of parks' carbon fluxes should be taken into account in the network model. The system boundary does not just coincide with the administrative boundaries, but a virtual boundary that contains metabolic processes links both inside and outside of the park. Taking carbon metabolic processes and their relationship through different compartments within the virtual boundary, a metabolic network model for low-carbon high-tech industrial parks (we might call it as Low-Carbon Metabolic Network (LCMN) as well) is established for tracking carbon flows within an low-carbon park ecosystem (Figure 1). In the LCMN, it embraces seven individual compartments: energy supporting sector (Eng), construction sector (Con), industry, business and service sector (IBS), waste management sector (Wst), green project sector (Grn), internal environment (Int), and external environment (Ext). Diverse carbon fluxes running through these compartments are identified and characterized as the compartmental interactions within LCMN, including the flows within Eng, Con, IBS, and Wst in terms of exchanging materials (both goods and wastes) and energy, flows between the park and its external environment, and the natural carbon exchange of the park. Besides, the flow of goods transporting and transport fuel induced by BDA (within and outside the park) were also involved.

2.2. Ecological Network Analysis

2.2.1. Network Utility Analysis (NUA). "Utility" is an economic conception similar to "efficiency." Since Patten [29, 30] firstly introduced the concept of NUA, it has mainly been applied to indicate both qualitative and quantitative exchange-based relationships between different compartments of a network system [27]. The relation forms within components are in variety, where one of the simplest ideas is sorted as direct and indirect (similar as a series of consequent direct transfer). In NUA, direct and integral relationships are expressed by a direct utility matrix $\mathbf{D}$ and dimensionless integral utility intensity matrix $\mathbf{U}$, respectively. Matrix $\mathbf{D} = [d_{ij}]$ illustrates the relative strength of direct input and output control in the network [27]. d_{ij} represents the direct interactions between compartment i and j, which can be expressed as

$$d_{ij} = \frac{\left(f_{ij} - f_{ji}\right)}{T_i}, \tag{1}$$

where f_{ij} represents the metabolic flow (e.g., carbon flow) from compartment j to i; T_i is the sum of input or output flows for the ith compartment at the steady state. Then, whole-system, integral, utility-based relations are given by considering all the indirect influences in the network carried by the higher-order interactions [31]. Distinguished with the direct utility matrix $\mathbf{D}$, integral utility intensity matrix $\mathbf{U}$ contributes to reveal the strength of the entire network organization. Compared with the sum of elements between the direct and indirect matrix, it could often find a greater contribution from indirect processes than from the direct one [27]. For revealing the net utility of each compartment to make use of materials along different-step pathways, matrix $\mathbf{U}$ is computed as

$$\mathbf{U} = \mathbf{D}^0 + \mathbf{D}^1 + \mathbf{D}^2 + \cdots + \mathbf{D}^m = (\mathbf{I} - \mathbf{D})^{-1}, \tag{2}$$

where $\mathbf{U}$ shows the utilities conveyed by pathways in different lengths $1, 2, \ldots, m$ (m is the total number of compartments, $m \geq 2$); the identity matrix $\mathbf{I}$ shows the self-feedback of flows through each compartment; the matrix $\mathbf{D}^1$ reflects the direct interactions between components; $\mathbf{D}^m$ represents the indirect relations between components along m-length-pathway. In the view of common network analysis indirect interactions $\mathbf{D}^k$ ($2 \leq k \leq m$) means specific materials convey via relative longer pathways greater than length one, which can be verified by taking the higher order powers of $\mathbf{D}$, for example, $\mathbf{D}^2$ gives utilities conveyed along two-step pathways, $\mathbf{D}^3$ is along three-step pathways, and so on [31].

In NUA, Sign D and Sign U are introduced as two sign matrices of $\mathbf{D}$ and $\mathbf{U}$ in order to reveal the mutualism relationship between components. Compared with Sign D, Sign U gives a deeper perspective in revealing potential connections between each component. Referring to the gain (+), loss (−), or neutrality (0), interactions can be calculated by two objects: (+, +) stands for mutualistic condition, (+, −) for exploitation condition, (−, +) for exploited condition, (−, −) for competition, and (0, 0) for neutrality [31]. In these two matrices, the sign changing would affect the interactions between components, and then affect the network structure.

Fath and Patten [27] then investigated network synergism (also known as mutualism), another NUA property, to convey that positive utility was more than negative utility in quantity. There are two ways for testing the network synergism: one of them can be quantified by total utility in the dimensional utility matrix, while another one is revealed by the ratio of positive to negative utility in the network system [27]. Hence, at the level of entire system, network mutualism index (MI) and synergism index (SI) are adapted to show the fitness of the whole-system [32–34]. MI reflects the ratio of the number of positive and negative signs in the Sign U. While SI quantifies the total magnitude of the positive and negative utilities, which assess the mutualistic condition of a system in slightly different angles [35]. If MI is greater than one, or SI is greater than zero, the system mutualism could occur [27, 29, 30]. MI and SI are computed as

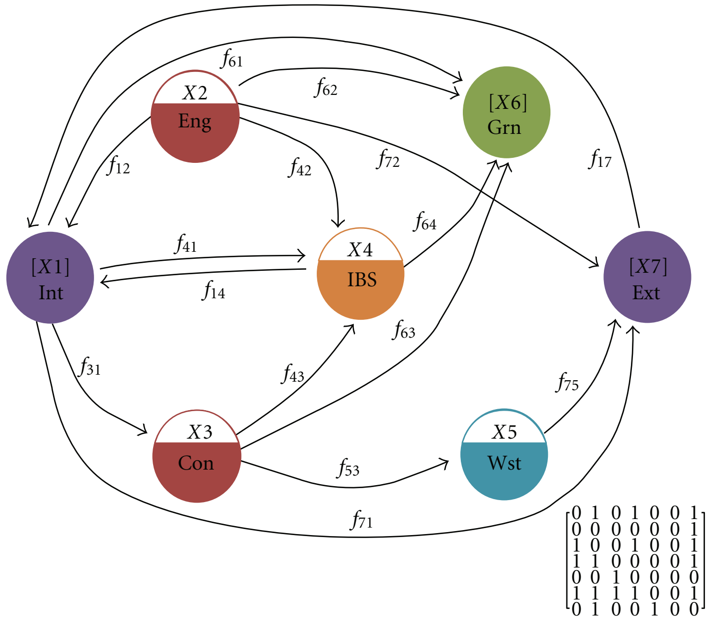
$$\mathrm{MI} = \frac{\mathrm{Sign}U(+)}{\mathrm{Sign}U(-)}, \tag{3}$$

$$\mathrm{SI} = \sum_{j=1}^{n}\sum_{i=1}^{n} u_{ij}, \tag{4}$$

where

$$\begin{aligned} \mathrm{Sign}U(+) &= \sum_{ij} \max\left(\mathrm{Sign}\left(u_{ij}\right), 0\right), \\ \mathrm{Sign}U(-) &= \sum_{ij} -\min\left(\mathrm{Sign}\left(u_{ij}\right), 0\right). \end{aligned} \tag{5}$$

2.2.2. Network Control Analysis (NCA). Patten [36] introduced NEA-based measures of control or dominance by using the input and output environ concept to develop a control matrix [37, 38]. Network control is based on a pair of integral flow through network flow analysis, which indicates the control from system compartments in the configuration



Int: internal environment
Eng: energy supporting sector
Wst: waste management sector
Con: construction sector
IBS: industry, business, and service sector
Grn: green project sector
Ext: external environment
f_{ij}: carbon flow from j to i
$[Xi]$: stock in environment
Xi: storage of sectors

Figure 1: Metabolic network model for carbon metabolism of BDA International Business Park. The matrix at the right bottom is the adjacency matrix A of the model, where $A = [a_{ij}]$. If there exists a carbon flow from compartment j to i, $a_{ij} = 1$, else $a_{ij} = 0$.

of the whole system [35]. And network flow analysis is predicated on a conceptual flow model of a system, revealing both the structure and function of the system [39].

Be similar as the direct utility matrix D and integral utility matrix U, in control analysis (or flow analysis), flow interactions can also be divided into direct and integral (including initial input, direct, and indirect interactions) ones. Matrix $\mathbf{G}$ is the direct interaction matrix, giving the functional influences due to all paths of lengths commensurate with the power. While matrix $\mathbf{N}$ shows the indirect interaction, summing the infinite power series of the direct interaction matrix [39].

For the output environ, from the generating or flow-forward transfer efficiencies and the receiving or flow-backward transfer efficiencies $\mathbf{G} = [g_{ij}]$ and $\mathbf{G}' = [g'_{ij}]$, dimensionless integral output and input flow intensity matrices $\mathbf{N} = [n_{ij}]$ and $\mathbf{N}' = [n'_{ij}]$ can be computed as

$$\mathbf{N} = \left[n_{ij}\right] = (\mathbf{I} - \mathbf{G})^{-1}, \qquad \mathbf{N}' = \left[n'_{ij}\right] = (\mathbf{I} - \mathbf{G}')^{-1}, \tag{6}$$

where $g_{ij} = f_{ij}/T_j$, it shows the nondimensional, output-oriented, intercompartmental flows; if $g'_{ij} = f_{ij}/T_i$, it shows the input-oriented, intercompartmental flows [32, 38]. So two distributed control metrics based on these could be established to reflect the control and dependence condition, which are control allocation (CA) and dependence allocation (DA)

$$\mathrm{CA} = \left[ca_{ij}\right] \equiv \begin{cases} n_{ij} - n'_{ij} > 0, & ca_{ij} = \dfrac{n_{ij} - n'_{ij}}{\sum_{i=1}^{m} n_{ij} - n'_{ij}} \\ n_{ij} - n'_{ij} \le 0, & ca_{ij} = 0, \end{cases} \tag{7}$$

$$\mathrm{DA} = \left[da_{ij}\right] \equiv \begin{cases} n_{ij} - n'_{ij} > 0, & da_{ij} = \dfrac{n_{ij} - n'_{ij}}{\sum_{i=1}^{m} n_{ij} - n'_{ij}} \\ n_{ij} - n'_{ij} \le 0, & da_{ij} = 0, \end{cases} \tag{8}$$

where $0 \le da_{ij}, ca_{ij} \le 1$. By definition both CA and DA are calculated by the difference of two pairwise integral flows (i.e., n_{ij} and n'_{ij}). ca_{ij} reflects the degree that compartment j controls compartment i based on the controller's output environ, while da_{ij} indicates the degree that compartment j is dependent on compartment i from the observer's input environ.

Based on the network control and dependence formulation, the system-wide control condition can be revealed by the system control index (CI). CI combines control degree with dependence degree, and thus it indicates the control utility and organization capability of the whole system and can be employed to index the self-regulation of system metabolism [35] as follows:

$$\mathrm{CI} \equiv \frac{\sum_{j=1}^{m}\sum_{i=1}^{m} ca_{ij} + \sum_{j=1}^{m}\sum_{i=1}^{m} da_{ij}}{m^2}. \quad (9)$$

2.2.3. System-Wide Indicators. For the purpose of giving an overall perspective on metabolic performance of industrial park and contributing to design a both sustainable and low-carbonic park, it is necessary to define a set of indicators in addressing the system performance of the MN. Some of these indicators have already been introduced by NUA and NCA as above, while others were extracted from other researches of ENA [28]. Each indicator reflects a facet of carbon metabolism in LCMN for BDA. The formulations and short description of the whole-system indicators were illustrated (Table 1).

2.3. Data Source. The metabolism data sources were extracted from construction and operation data of BDA which were all calculated based on the IPCC recommended method and life cycle analysis. These data originated from investigations and calculation into carbon composition of artificial activities, raw materials' transportation, the relationships between these flows and stocks, and also within anthropogenic-natural processes.

3. Results

3.1. Ecological Structure of Carbon Emissions. Carbon fluxes between two compartments within LCMN of BDA are listed in Table 2. The result shows that Con (11.2%), Eng (8.2%), and Wst (8.2%) are three major carbon donors providing carbon to Con (41.4%) and Grn (24.5%), two major carbon accepters, in the form of materials, wastes, fossil fuels and machinery, and so forth. Diverse carbon exchanges between these major donors and accepters make a great contribution to support the operation of the park. Yet Eng and Wst's (both 8.2%) contribution in accepting carbon are not as great as their superior performance on the supply side. Compared with these major sectors, IBS as one of the most inactive sectors is both inferior in supplying and accepting carbon (3.9% and 6.7% resp.,). The ultimate suppliers and recipients of carbon are Int and Ext. Among which, both supplying and receipting of Int are not as much as other sectors (3.8% and 4.3% resp.,) showing a weak effect on the LCMN of BDA; Ext has a better performance in supplying (64.7%) than accepting carbon (8.9%), indicating the BDA park may be more dependent on the supply of the external environment. The biggest carbon emissions are from Eng to Int (3046 t CO_2-eq) and Wst to Ext (17547 t CO_2-eq). And IBS (6001 t CO_2-eq) and Grn (2176 t CO_2-eq) are two major sectors obtaining carbon from internal environment, which are much more than Con (13 t CO_2-eq). Similarly, Con (82509 t CO_2-eq), Grn (39620 t CO_2-eq), and Eng (12796 t CO_2-eq) are all extracting carbon greatly from the external environment, revealing that these three main sectors are more dependent on external supply again. The carbon emission (from Wst to Ext, 8.2%), extraction (from Ext to Con, 38.6%), and processing (from Con to Wst, 8.2%) are the most active and significant processes. Overall, the total carbon through flow of BDA is 213670 t CO_2-eq.

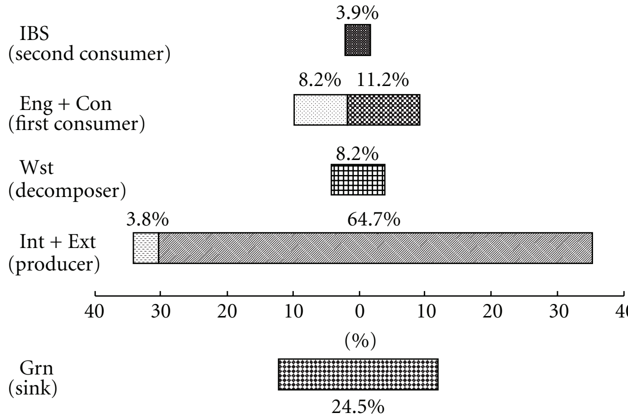


Figure 2: Ecological structure of carbon metabolism in BDA.

The proportion of carbon flows within each sector can reflect the ecological structure of the carbon metabolism in BDA, which forms an approximate pyramidal shape (Figure 2). In natural ecosystem, the pyramidal trophic structure based on the food web is one of the most stable structures leading an ordered and healthy ecosystem. In this sense, the carbon metabolic system in BDA is also in stable condition relatively in the role of producer (Int and Ext), decomposer (Wst), first consumer (Eng and Con), and second consumer (IBS). Besides, as a little deficiency, the decomposer cannot take full advantage thanks to the limit of waste managing technology. If we enhance the role of decomposers in the BDA's carbon metabolic network, the utilization efficiency and system stability of carbon metabolism will be improved.

Reading from left to right, the values are the total carbon inputs or outputs (Grn fits the output value) of compartments. Producer: supplying distal carbon into BDA system; decomposer: releasing carbon for producers' reuse by decomposition of the waste; first consumer: carbon agents that transfer carbon from natural environment to human society; second consumer: anthropogenic using processed carbon resources from first consumers by processes of creating products or utilizing energy; sink: eliminating carbon through photosynthesis of green trees, it does not belong to the trophic structure.

3.2. Network Mutual Relationships. Table 3, respectively, shows the direct mutual relationships (in the matrix Sign D) and integral interactions (in the matrix Sign U) between such compartments of LCMN in BDA. It is apparently that the positive/negative signs in the matrix Sign U sometimes vary from those in the matrix Sign D, which implies that both quantities and qualities of the integral relationships could alter compared with those direct ones [27]. By comparing the relation changes between direct and integral utility matrix, it is obvious that circumstances of no changes occur most

Table 1: System-wide indicators of metabolism model.

Indicators	Formulation	Short description
Nodes	m	Quantity of metabolic compartments, also the size of network
Links	L	Quantity of metabolic direct flows or arcs
Link density	L/m	Metabolic linking degree
Connectance	L/m^2	Metabolic connectivity, also the proportion of realized direct pathways
MI	Equation (3)	Metabolic system
SI	Equation (4)	Metabolic system synergism
CI	Equation (9)	Self-regulation of metabolism

Table 2: Carbon flows within the low-carbon metabolic network of BDA (unit: t CO_2-eq)[a].

Doner/accepter	Int	Eng	Con	IBS	Wst	Grn	Ext	T_j
Int	0 (0.0%)	3046 (1.4%)	0 (0.0%)	39 (0.0%)	0 (0.0%)	0 (0.0%)	6014 (2.8%)	9100 (4.3%)
Eng	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	12796 (6.0%)	12796 (6.0%)
Con	13 (0.0%)	0 (0.0%)	0 (0.0%)	6001 (2.8%)	0 (0.0%)	0 (0.0%)	82509 (38.6%)	88523 (41.4%)
IBS	6001 (2.8%)	8288 (3.9%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	23 (0.0%)	14312 (6.7%)
Wst	0 (0.0%)	0 (0.0%)	17547 (8.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	17547 (8.2%)
Grn	2176 (1.0%)	4644 (2.2%)	6408 (3.0%)	2234 (1.0%)	0 (0.0%)	0 (0.0%)	36920 (17.3%)	52382 (24.5%)
Ext	0 (0.0%)	1462 (0.7%)	0 (0.0%)	0 (0.0%)	17547 (8.2%)	0 (0.0%)	0 (0.0%)	19009 (8.9%)
T_i	8190 (3.8%)	17441 (8.2%)	23955 (11.2%)	8274 (3.9%)	17547 (8.2%)	0 (0.0%)	138262 (64.7%)	**213670**

[a]The numbers in parentheses mean the proportion of carbon flows, namely, the flow value divided by the total carbon flow in the whole system. T_i is the sum of flows put into the j-th compartment, and T_j is for the sum flows into the j-th compartment analogously. The T_i-T_j intersecting number in bold indicates the total carbon flow of BDA.

frequently, that is, the relationship of IBS-Int (−, +), Eng-Ext (−, +), Con-Wst (+, −), and etc. and the next is those changes to the positive side, that is, the relationship between Con and Int varies from (0, 0) in direct to (+, +) in integral, and so does between Ext-Int, Eng-Wst, IBS-Wst, and Wst-Ext. Such result indicates that relationships between compartments are more prone to system-wide stability and benefits.

Then, we tried to analyze each trophic level. There are some differences in respective mutual relations between producers (Int and Ext). Int has a variety of links and its direct and integral relationships are not unified. Both the direct and indirect linkages for Ext mainly indicate that it exploits consumers (Eng, Con, and IBS) in terms of advancing raw materials, apparatus, and energy, and then being exploited by decomposer (Wst) for carbon recycle. As the largest carbon doners, Ext dominates the contacts between producers and other compartments. The irreplaceable effect of decomposer leads to obvious direct relationships that Wst is exploited by first consumer (Con) in dealing with carbon waste and pays back to producer (Ext). Besides, there are no more direct links between other consumers and producer but diverse indirect interactions. First consumers (Eng and Con) play a significant role in transform carbon from distal environment

Table 3: Direct utility sign matrix (Sign D)/integral utility sign matrix (Sign$U$) of LCMN in BDA[a].

	Int	Eng	Con	IBS	Wst	Ext
Int	0/+	+/−	0/+	−/−	0/−	0/+
Eng	−/−	0/+	0/−	−/−	0/+	+/+
Con	0/+	0/−	0/+	+/+	−/−	+/+
IBS	+/+	+/+	−/−	0/+	0/+	0/−
Wst	0/+	0/+	+/+	0/+	0/+	−/+
Ext	−/+	−/−	−/−	0/−	+/+	0/+

[a]Due to the value of total supplied carbon from Grn is zero, as the carbon sink, we can consider that the mutual relationships between other compartments and Grn are exploit-exploited (including Int, Eng, Con, IBS, and Ext) or neutrality (including Wst). In this sense, we did not take into consideration Grn calculation and comparison in Table 3. In addition, the signs of direct and integral utility matrixes for each pair of compartments are separated by "/", for example, "+/−" and "−/−" between Eng and Int show that the direct mutual relationship between them is (+, −), while the integral interaction is (−, −).

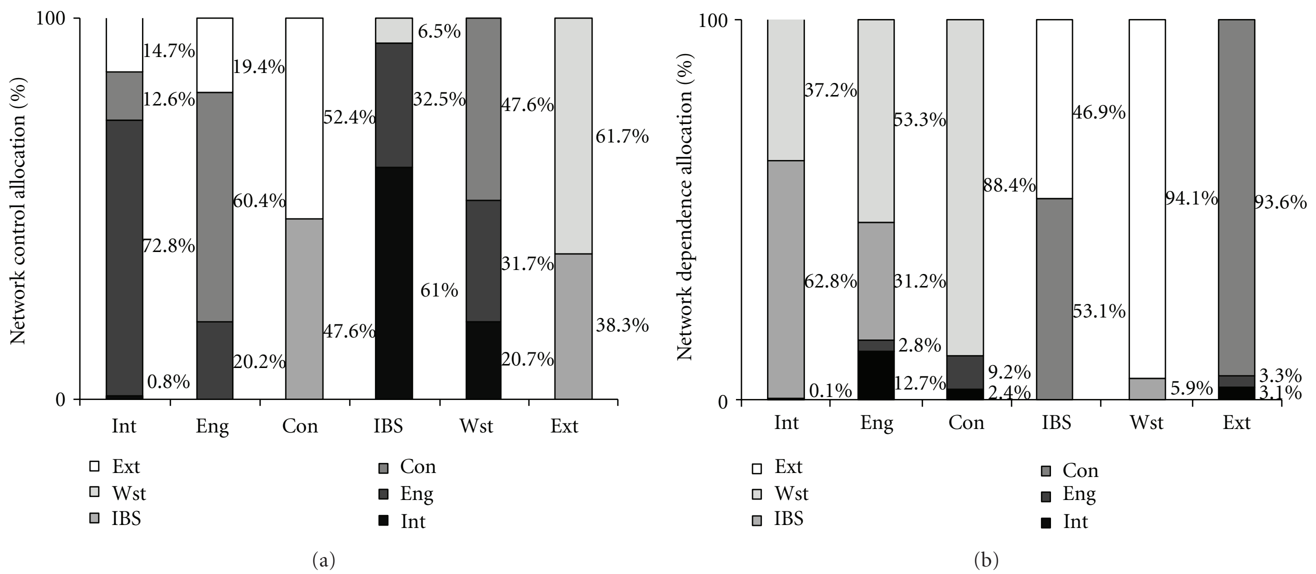


Figure 3: (a) Network control of carbon metabolism in BDA. (b) Network dependence of carbon metabolism in BDA. Because the value of total supplied carbon from Grn is zero, we did not consider the influence from Grn in these figures for an easy calculation.

into industrial society, so they mainly exchange carbon with producer (especially Ext) in terms of raw materials and energy. And particularly, Con is exploited by producer and second consumer (IBS) in material import and service management. Located at the highest trophic level, utility consumer (IBS) is mainly exploited by producer (Int and Ext) and first consumers (Eng and Con), for it acts better as a carbon recipient. Yet the direct and integral relationships between IBS and the decomposer (Wst) are in neutrality and mutualistic condition. That is because there is no direct carbon exchange between them, while both of them are exploited by Con as a carbon accepter in indirect ways. In a word, these compartments all play their own role in ecological structure of carbon metabolism in BDA.

3.3. Network Control Condition. Figures 3(a) and 3(b) illustrate the proportion for control and dependence condition of LCMN in BDA, respectively. These proportions are extracted from the control allocation matrix (CA) and dependence allocation matrix (DA) introduced in the preceding part, which indicates the control degree based on the controller's output environ and dependence degree from the being controlled input environ.

From the dependent perspective, Eng and Con as first consumers have some differences on dependence degree, and there exists an intrinsic linkage. Eng is more controlled by Con (60.4%), while Con is dependent on second consumer's management (IBS, 47.6%). The second consumer (IBS) generally depends on Eng's energy furnish (32.5%), whereas the influence from Wst (6.3%) is too small to mention. And at the decomposer's level (Wst), the control degree is mostly contributed by first consumers, where Con achieves 47.6% and Eng as 31.7%. The control condition shows a similarity (even more pronounced) in the systemic control for carbon

Table 4: System-wide indicators of carbon metabolism in BDA.

Indicators	Formulation	Low-carbon metabolic network with Int and Ext	without Int and Ext
Nodes	m	7	5
Links	L	15	6
Link density	L/m	2.14	1.20
Connectance	L/m^2	0.31	0.24
MI	Equation (3)	1.50	1.40
SI	Equation (4)	3.57	2.54

metabolic in the views of controller. In addition, by observing the producers dependence degree, first consumers are more dominated by Ext (Eng is 19.4%, while Con is 52.4%), while second consumer (IBS, 61.0%) and decomposer (Wst, 20.7%) are more controlled by Int. Similar results have also been reflected in the control condition, where the control proportions from Ext to IBS and Wst reach 46.9% and 94.1%, while those from Int to Eng and Con achieve 12.7% and 2.4%. These similar results announce that the BDA International Park is further regulated by the outside world (especially by the external environ), so as to enhance the integral cooperation between those compartments, which may be a promising way to improve the utility of carbon metabolic in BDA.

3.4. System Condition. The calculating values of system-wide indicators for carbon metabolism in BDA are all shown in Table 4. Apparently, compared with the carbon flows without internal and external environment, there are more connections among network compartments. Similar results are also shown in the Link Density and Connectance, where suggesting that with cooperation of Int and Ext, there are more diverse cycling ways. These results emphasize the significant affection and higher efficiency of producers (Int and Ext). Moreover, the whole system properties of LCMN in BDA have higher MI (1.50) and SI (3.57), indicating the industrial system holds more positive relationships in an integral way. Due to the fact that Mi is >1.00 both with and without Int and Ext, the carbon metabolic system in BDA can maintain self-mutualism and sustainability despite the lack of external supply. In natural ecosystem, it is quite often the case that more positive utilities than negative ones are needed to keep self-mutualism [31]. Making an analogy with natural ecosystem, these results may evince a sustainable improvement of carbon metabolism in BDA International Business Park.

4. Conclusions

Based on the methodology of ENA, we established a metabolic model for low-carbon high-tech industrial parks and analyzed the carbon metabolic system of the BDA International Business Park in this research. The results reflected the behaviors and potential linkage of system compartments and revealed the structure, function, and mutualism condition of the carbon metabolic system in the case park. In the relationship and control analyses, compartments links are quite diverse and positive, especially the Con and Wst, which play a pivotal role in exchanging carbon flows between industrial compartments and environs (both Int and Ext). Comparing the scenarios with Int and Ext or not, variations of system-wide indicators have revealed the significance of artificial control including carbon supplying and decomposing. Regarding ecological structure and function, the pyramidal ecological structure and positive indicators (MI and SI) both show a system mutualism and sustainable condition, which makes BDA Park a demonstration project in Chinese low-carbon EIPs' construction. Yet if we enhanced the effect of waste management part, different system functions would go on better.

Acknowledgments

This study was supported by Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant No. 51121003), Key Program of National Natural Science Foundation (NOs. 50939001, 41271543), and Program for New Century Excellent Talents in University (NCET-09-0226). We are especially grateful for the financial support from Beijing Development Area Co. Ltd.

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The Scientific World Journal
Volume 2012, Article ID 841636, 7 pages
doi:10.1100/2012/841636

The ScientificWorldJOURNAL

Research Article

Case Study on Incentive Mechanism of Energy Efficiency Retrofit in Coal-Fueled Power Plant in China

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Received 6 September 2012; Accepted 31 October 2012

Academic Editors: B. Chen, Z.-M. Chen, and H.-S. Tang

An ordinary steam turbine retrofit project is selected as a case study; through the retrofit, the project activities will generate emission reductions within the power grid for about 92,463 tCO_2e per annum. The internal rate of return (IRR) of the project is only −0.41% without the revenue of carbon credits, for example, CERs, which is much lower than the benchmark value of 8%. Only when the unit price of carbon credit reaches 125 CNY/tCO_2, the IRR could reach the benchmark and an effective carbon tax needs to increase the price of carbon to 243 CNY/tce in order to make the project financially feasible. Design of incentive mechanism will help these low efficiency enterprises improve efficiency and reduce CO_2 emissions, which can provide the power plants sufficient incentive to implement energy efficiency retrofit project in existing coal-fuel power generation-units, and we hope it will make a good demonstration for the other low efficiency coal-fueled power generation units in China.

1. Introduction

With the rapid development of industrialization and urbanization, the global climate-change issue has become an important factor to affect the world economic order, political regime and international relations, as well as to determine the key of the world's energy future [1, 2]. Global climate change is closely related to energy, a variety of greenhouse gases (GHG) that cause climate change. Carbon dioxide (CO_2) contribution rate is more than 50%, and 70% of human activities' CO_2 emissions are from the burning of fossil fuels [3]. At present, China is one of the countries with the most CO_2 emissions in the word, and CO_2 emissions are still growing rapidly. The main reasons for CO_2 emissions of China are as follow: (1) The existing energy resource characteristics of primary energy consumption are dominated by coal, and thermal power accounts for about 70% of the total power generation; (2) the rate of energy-intensive industries and products is high [4].

In the 12th Five-Year Plan, China has shown its intention to shift from a policy of maximizing growth to balance growth with social harmony and environmental sustainability [5]. But the dominant position of coal in the energy consumption will continue in a long period; by 2020, the GDP goal is quadrupling, and then the total installed capacity will reach 900–950 million kilowatts, generating capacity will reach 4.2 trillion kWh, of which thermal power installed capacity still contains about 70%. How to coordinate the relationship between the rapid development with CO_2 emissions is a severe challenge for the power industry.

Today, there are lots of low efficiency power plants in China, which is urgent to implement the steam turbine retrofit, and these power plants have the great potential to reduce CO_2 emissions. Because the development among different regions and industries in China is very uneven, the enterprises cannot afford the high cost of the steam turbine retrofit by themselves [6]. The introduction of an incentive mechanism to help these low efficiency enterprises to improve efficiency and reduce CO_2 emissions has been practically significant [7]. In this study, a steam turbine retrofit project in China is selected for a case study to find an effective GHG emission reduction mechanism for this project type, which can provide the power plants sufficient incentive to implement energy efficiency retrofit project in existing coal fuel-power generation-units, and we want to make a good demonstration for the other low efficiency coal-fuel power generation-units in China.

2. Description of the Project Activity

2.1. Site Description. Panshan Power Plant is located in the southeast of the Ji County, Tianjin City (117°16′58′′E, 39°59′26′′N). The mean annual temperature in Ji County is 10-11°C, and the mean annual precipitation is approximately 700 mm, of which three-quarters are distributed from July to September. Figure 1 is the location of Panshan Power Plant.

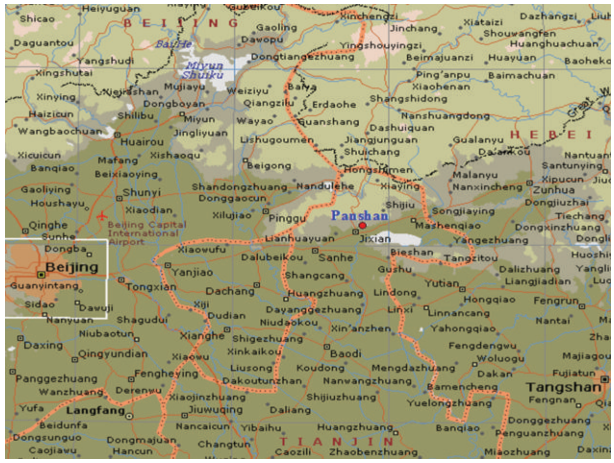

Figure 1: The map of the project location–Panshan Power Plant.

2.2. Description of the Project. Steam Turbine Retrofit Project of Tianjin Panshan Power Plant (hereafter refers to as the project) involves retrofitting supercritical steam turbine. The steam turbine with rated power of 500 MW (hereafter refers to as PAT, project activity turbine), which was designed in the early 1970s and introduced from Russia, has been put into commercial operation since April 16th 1996. The technical lifetime of the power unit is 24 years. Designed as a super critical turbine set, the technological level of the PAT is relatively higher than the subcritical turbine sets that are commonly used and regarded as a good practice currently in current China. So up to 2009 (the year of retrofit action), the remaining life is 11 years, more than 8 years. The principal specifications of the steam turbine are shown below (Table 1).

The main target of the project is retrofitting the low pressure cylinder to reduce the coal consumption of the power generation, in particular, by promoting the performance of the low pressure cylinder. The components, including rotor, blades, diaphragm and its set, inner cylinder, and shaft butt seal of the low pressure cylinder, are retrofitted. Steam seal installed in the surrounding bend of the first stage of high-pressure cylinder, steam seal of each turbine stage, and shaft butt seal of high-cylinder and medium-cylinder will also be altered (Figure 2).

The current practice with low efficiency would be continued in the absence of the proposed project. By adopting retrofit measures, the proposed project will not only reduce GHG emissions, but also contributes to sustainable development for local communities by the means of: (1) reducing the emissions of SO_2, NO_x, and coal ash due to the reduction of standard coal consumption; (2) improving the energy efficiency of power plant and promoting development of manufacturing industry. The project is expected to give a lead on turbine retrofit of supercritical power plants in China.

3. Performance Assessment

3.1. Emission Reductions. To evaluate the effect of GHG emission reduction by the project with a quantitative way, the approved CDM methodology AM0062 in Unit Nation Framework Convention on Climate Change (UNFCCC) is applied to this study on the project in the following steps: calculate the baseline emissions, the project emissions, and the emission reductions [8].

3.1.1. Calculate the Baseline Emissions. (1) Determine baseline emission for the scenario of project electricity generation. Electricity generation in the project power plant will displace in the baseline scenario less efficient electricity generation in the project plant and can, in addition, displace electricity to the grid, if the quantity of electricity generation is increased as a result of the project. The calculation of baseline emissions is therefore based on different emission factors for different quantities of electricity generated. In China the annual power generation is determined by the annual dispatch order from grid company where the PAT connects to, thus it is assumed that annual power generation dispatch will be according to the original capacity of PAT. In this case, the annual power generation after retrofit unlikely exceeds the historical average level. Therefore the emission reduction is only relevant to the efficiencies of PAT before and after the retrofit.

To evaluate the emission reduction due to the retrofit, the follow case from AM0062 [9] is selected in a future analysis: the quantity of electricity generated in the project turbine ($EG_{PJ,y}$) is lower or the same as the historic average annual generation level (EG_{AVR}). Baseline emissions are calculated as:

$$BE_y = EG_{PJ,y} * EF_{BL,y}, \tag{1}$$

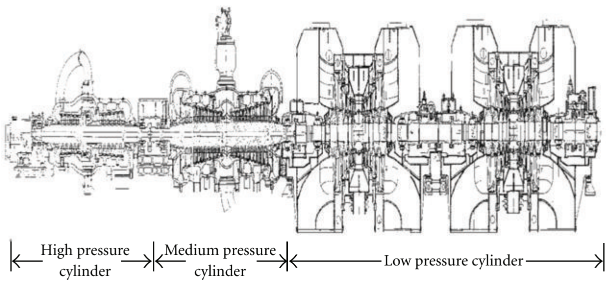

FIGURE 2: Profile of turbine.

TABLE 1: The principal specifications of the steam turbine.

Item	Designed value
Manufacturer	Leningrad metal factory of Russia (designed in the beginning of 1970s)
Type of turbine	Supercritical, once reheated, single shaft, 4 cylinder and 4 steam exhaust, condensing turbine
Rated power	500 MW
Rated main steam flow	1528.8 t/h
Main steam pressure	23.54 MPa
Main steam temperature	540°C
Reheated steam pressure	3.51 MPa
Reheated steam temperature	540°C
Exhausted steam pressure	4.27/5.44 kPa
Number of blade stage	54
Net heat rate	8146 kJ/kWh
Lifetime	24 years

where BE_y = baseline emissions in year "y" (tCO_2/yr), $EG_{PJ,y}$ = quantity of electricity supplied by the project turbine to the grid in year "y" (MWh/yr), adjusted for changes in efficiency, $EF_{BL,y}$ = baseline emission factor of the project turbine in year y (tCO_2/MWh).

(2) Determine Baseline Emission factor. The project turbine is steam turbine and the fuel is fired in a boiler, so its emission factor is calculated as follows [10]:

$$EF_{BL,y} = \frac{3.6}{1000} \times \frac{EF_{FF,BL} \times FC_{PJ,y} \times NCV_{FF,PJ}}{\eta_{BL,y} \times HI_{PJ,y}}, \quad (2)$$

where $EF_{BL,y}$ = baseline emission factor of the Project turbine in year "y" (tCO_2/MWh), $EF_{FF,BL}$ = CO_2 emission factor of the fossil fuel used in the Project turbine prior to the implementation of the Project (tCO_2/TJ), $NCV_{FF,PJ}$ = net calorific value (NCV) of fossil fuel used in the Project turbine during year y (TJ/tonne of fuel).

$\eta_{BL,y}$ = energy efficiency of the turbine without retrofitting estimated using the latest version of approved "tool to determine the baseline efficiency of thermal or electric energy generation systems," determined the efficiency based on measurements and used a conservative value, based on performance tests before the implementing the project following national/international standards, at discrete loads within the operating range or over the entire rated capacity, $FC_{PJ,y}$ = Actual fuel consumption by project in year "y" (tonne of fuel), $HI_{PJ,y}$ = Heat input to the steam turbine in year "y" (TJ). In case of multicylinder steam turbines, this is the sum of the heat input at the inlet of first stage and the heat inputs in the re-heaters of steam between various cylinders (e.g., high-pressure, medium pressure, and low-pressure cylinders).

3.1.2. Calculate the Project Emissions. The CO_2 emissions from fossil fuel consumption in the project (PE_y) should be calculated using the latest approved version of the "tool to calculate project or leakage CO_2 emissions from fossil fuel combustion," where the process j in the tool corresponds to the combustion of fossil fuels in the project for electricity generation in the project power plants [11]:

$$PE_{FC,j,y} = \sum_i FC_{i,j,y} \times COEF_{i,y}, \quad (3)$$

where $PE_{FC,j,y}$ = are the CO_2 emissions from fossil fuel combustion in process j during the year y, $FC_{i,j,y}$ = is the quantity of fuel type i combusted in process j during the year y (mass or volume unit/yr), $COEF_{i,y}$ = is the CO_2 emission coefficient of fuel type i in year y (tCO_2/mass or volume unit), i = are the fuel types combusted in process j during the year y.

The CO_2 emission coefficient $COEF_{i,y}$ can be calculated using one of two proposed in the "tool to calculate project or leakage CO_2 emissions from fossil fuel combustion".Depending on the availability of data on the fossil fuel type i, the CO_2 emission coefficient $COEF_{i,y}$ is calculated based on net calorific value and CO_2 emission factor of the fuel type i:

$$COEF_{i,y} = NCV_{i,y} \times EF_{CO_2,i,y} \quad (4)$$

where $COEF_{i,y}$ = is the CO_2 emission coefficient of fuel type i in year y (tCO_2/mass or volume unit), $NCV_{i,y}$ = is the weighted average net calorific value of the fuel type i in year y (GJ/mass or volume unit). $EF_{CO_2,i,y}$ = is the weighted average CO_2 emission factor of fuel type i in year y (tCO_2/GJ), i = are the fuel types combusted in process j during the year y.

3.1.3. Calculate the Emission Reductions. (1) Emission reductions are calculated as follows:

$$ER_y = BE_y - PE_y, \quad (5)$$

where ER_y = emissions reductions in year y (tCO_2e/yr), BE_y = baseline emissions in year y (tCO_2e/yr), PE_y = project emissions in year y (tCO_2e/yr).

(2) Data and parameters which are available at validation. Because the regional specific value is not available, the Intergovernmental Panel on Climate Change (IPCC) default value of the CO_2 emission factor of coal was selected. Choose the CO_2 emission factor corresponding to the applicable fuel type. IPCC default values may be used. CO_2 emission factor of the fossil fuel used in the Project turbine prior to the

Table 2: The key parameters of the project.

Item	Value	Unit	Data source
Electricity supplied to the grid in year y ($EG_{PJ,y}$)	2,632,000	MWh	Feasibility study report of the project (FSR)
Standard coal consumption after retrofit	322.5956	kg/MWh	Efficiency test report
Net calorific value of standard coal	29,306	MJ/ton	Efficiency test report
Net calorific value of fossil coal	23,026	MJ/ton	Calculated
Annual consumption of fossil coal	1,080,643.24	ton	Calculated
Average net heat consumption of turbine after retrofit	8738.92	kJ/kWh	Efficiency test report

implementation the Project ($EF_{FF,BL}$) = 89.5 tCO_2/TJ of fuel [12].

Use the latest version of approved "tool to determine the baseline efficiency of thermal or electric energy generation systems." Depending upon the option selected from the latest version of approved "tool to determine the baseline efficiency of thermal or electric energy generation systems." Energy efficiency of the turbine without retrofitting in a year y($\eta_{BL,y}$) = 39.553% (from Efficiency Test Report of the PAT prior to the retrofit).

(3) Ex-ante calculation of emission reductions. In order to estimate the emission reductions generated by the project, the following assumptions are brought into account.

(4) Calculate the baseline emissions:

$$\begin{aligned} EF_{BL,y} &= \frac{3.6}{1000} \times \frac{EF_{FF,BL} \times FC_{PJ,y} \times NCV_{FF,PJ}}{\eta_{BL,y} \times HI_{PJ,y}} \\ &= \frac{3.6}{1000} \\ &\quad \times \frac{89.5 \times (322.5956 \times 2,632,000) \times 0.029306}{0.39553 \times 2,632,000 \times 8738.92} \\ &= \frac{0.88126\, tCO_2e}{\mathrm{MMh}}, \\ BE_y &= EG_{PJ,y} * EF_{BL,y} = 2,632,000 * 0.88126 \\ &= 2,319,482\, \mathrm{tCO_2}e. \end{aligned} \tag{6}$$

(5) Calculate the project emissions:

$$\begin{aligned} PE_y &= FC_{coal,y} \times NCV_{coal,y} \times EF_{CO2,coal,y} \\ &= 1,080,643.24\,\mathrm{ton} \times 0.023026\,\mathrm{TJ/ton} \\ &\quad \times 89.5\,\mathrm{tCO_2}e/TJ \\ &= 2,227,019\,\mathrm{tCO_2}e. \end{aligned} \tag{7}$$

(6) Calculate the emission reductions:

$$\begin{aligned} ER_y &= BE_y - PE_y = 2,319,482 - 2,227,019 \\ &= 92,463\,\mathrm{tCO_2}e. \end{aligned} \tag{8}$$

3.1.4. Summary of the Ex-Ante Estimation of Emission Reductions. It is expected that the project activities will generate emission reductions within the power grid for about 92,463 tCO_2e per annum over an 8-year fixed crediting period from 01/01/2012 to 31/12/2019. And the total emission reductions will come to 739,704 tCO_2e.

3.2. Investment Analysis

3.2.1. Determine the Suitable Financial Indicator for the Project Type. Financial indicator of internal rate of return (IRR) is the most suitable for such power retrofit project and decision making context. According to Trial Implementation Methods for Economic Assessment of technology retrofit Project in Power Engineering, the benchmark of IRR of power retrofit project is set at 8% [13]. The financial attractiveness of this project will be determined by comparing the IRR after tax (without Certified Emission Reductions (CERs)) with its benchmark applied in power retrofit project of China power industry, which is a standard recommended by the industry experts and is widely used at present in China. If the IRR after tax (without CERs) is less than 8%, the project is considered not being financially attractive in the absence of CDM revenues, and is therefore considered to be additional.

3.2.2. Calculation and Comparison of Financial Indicators. The key parameters of the project are showed in Tables 2 and 3.

The financial analysis results are shown in Table 4. As shown in this table, without carbon credits, the IRR is −0.41%, which is much lower than the benchmark rate of 8%. This therefore indicates that in comparison to other alternative investments, the project without carbon credits is not financially attractive to a rational investor.

3.2.3. Sensitivity Analysis. The sensitivity analysis is conducted to check whether, under reasonable variations of the sensitive factors in the critical assumptions, the results from the analysis remain unaltered. After overall checking of the IRR calculation sheet, five factors have been selected for the sensitivity analysis, which are the total investment, annual operation hours, electricity tariff, standard coal price, and the decrease of standard coal consumption.

Assuming the five factors within a fluctuation range from −20% to 20%, the IRR (after tax) of the project (without income from selling CERs) varies to a different extent, as shown in Table 5.

As shown in the sensitivity analysis, even the varying range of the uncertain factors reaches ±20%, the IRR (after tax) could not reach the benchmark. The conclusion that the

Table 3: The key parameters of the proposed project.

Item	Value	Unit	Data source
Rated continuous power	500	MW	FSR
Total investment	100,000,000	RMB	FSR
Equity proportion	100	%	FSR
Incremental annual power generation	0	MWh	FSR
Profit loss due to the retrofitting	24,730,000	RMB	FSR
Annual operation hours	5600	h	FSR
Power consumption rate (for self-use)	6	%	FSR
Standard coal consumption for power generation before retrofit (designed in FSR)	316	g/KWh	FSR
Decrease of standard coal consumption after retrofit (designed in FSR)	13	g/KWh	FSR, P51
Standard coal price (without VAT)	389	RMB/ton	FSR
Electricity tariff (without VAT)	341.2	RMB/MWh	FSR
New added O and M cost	−11,675,000	RMB/year	FSR
Of which fuel cost saving due to retrofit	−14,175,000	RMB/year	FSR
New added repair cost	2,500,000	RMB/year	FSR
Income tax	25	%	FSR
Value added tax (VAT)	17	%	FSR
Town building maintenance tax	7 (of VAT)	%	FSR
Surcharge for education	3 (of VAT)	%	FSR
Project operating period	11	Years	FSR
Rate of residual value of the fixed assets	3 (out of total investment)	%	FSR
Depreciation period	11	Years	FSR
Amount of CERs	92,463	tCO_2e/year	ER calculation sheet

Table 4: The financial indicators of the project.

Financial indicators	Rate
IRR (after tax) without CERs	−0.41%
Benchmark	8%
IRR with CERs	8.27%

project is definitely not financially attractive would not be influenced.

As above, the internal rate of return (IRR) of the project is only −0.41% without the revenue of carbon credits for example, CERs, which is much lower than the benchmark value of 8%. In addition, only when the unit price of carbon credit comes to 125 CNY/tCO_2, the IRR could reach the benchmark and become financially feasible. Therefore the GHG emission reduction cost of such retrofit project is 125 CNY/tCO_2.

3.3. Design of Incentive Mechanism

3.3.1. Incentive from Carbon Tax. Carbon tax is a Pigovian tax levied on the carbon content of fuels [14], which is a form of carbon pricing. Carbon is present in every hydrocarbon fuel (coal, petroleum, and natural gas) and is released as CO_2, when they are burnt [15].

In this case study, it is assumed that government levies the carbon tax on coal consumption in the power sector. It means that the carbon tax will be a part of the fuel cost in operating the power plant, being of the same effect of raising the price of coal. According to the sensitive analysis, an effective carbon tax needs to increase the price of coal by 243 CNY/tce, so as to make the project financially feasible. Then the cost of carbon tax should be 90 CNY/tCO_2 (1tce leads to GHG emission of 2.77 tCO_2).

3.3.2. Incentive from Carbon Market (Credit Trading). Emissions trading or cap-and-trade is a market-based approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants. For GHG the largest is the European Union Emission Trading Scheme (ETS), whose purpose is to avoid dangerous climate change [16]. In the carbon market created by ETS, GHG emission reduction credits are a kind of eligible unit, generated from the project that is implemented by entity outside the ETS. As analyzed above, the price of carbon credits in the market for example, CERs must be not less than 125 CNY/tCO_2 to make the project financially attractive.

3.3.3. Incentives Combined with Encouraging Dispatch Plan. Since the electricity tariff is determined by the government in China, which is fixed unless the new tariff policy approved by the government, most of the coal fuel power plants resist

Table 5: The sensitivity analysis of the project within a fluctuation range from −20% to 20%.

Fluctuation range	−20%	−10%	0	10%	20%
Total investment	2.34%	0.87%	−0.41%	−1.55%	−2.57%
Annual operation hours	−3.64%	−1.98%	−0.41%	1.08%	2.50%
Electricity tariff	−0.41%	−0.41%	−0.41%	−0.41%	−0.41%
Standard coal price	−3.64%	−1.98%	−0.41%	1.08%	2.50%
Decrease of standard coal consumption	−3.64%	−1.98%	−0.41%	1.08%	2.50%

Table 6: The necessary cost of carbon tax and credit price with/without encouraging dispatch plan.

Dispatch plan	Necessary cost of Carbon tax	Necessary cost of credit price
The dispatch electricity generation does not change	90 CNY/tCO_2	125 CNY/tCO_2
Dispatched electricity generation increased by 20%	50 CNY/tCO_2	85 CNY/tCO_2

carbon tax in practice. A very high cost of carbon tax is not very likely to occur in China. On the other hand, given the experience of the EU ETS, the credit price is of high volatility in the market [17]. Thus, there is always uncertainty about the credit price to make the investment decisions of this kind of retrofit. To mitigate the shortage of carbon tax and carbon market, the encouraging dispatch plan is expected to enhance the effect from above mechanisms.

Given the sensitivity analysis, the annual operation hours of the PAT are a very crucial factor to the IRR. The annual operation hours of a power plant are normally determined by power dispatch arrangement of grid company. In this section, the effect of encouraging dispatch plan is an analysis together with carbon tax and credit price in an ETS. Clearly, the more annual operation hours of the PAT, the higher IRR appears in the Project (Table 6). Thus, the necessary cost of either carbon tax and credit cost in ETS will decrease by incorporating with such encourage to dispatch plan.

4. Conclusions

This study presented the emission reductions of an ordinary thermal power plant after a steam turbine retrofit project with an incentive mechanism of carbon tax and carbon market (ETS). In particular, the most cost-efficient method is the combination of this mechanism made by central authorities with encouraging dispatch plan by grid company. The results presented within this paper indicate that the project will make a good demonstration for the other low efficiency thermal power plants in China.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (nos. 50908219 and 51209003), the Major Special Technological Program of Water Pollution Control and Management (no. 2010ZX07320-002), and Central Public-interest Scientific Institution Basal Research Fund (no. 0032012013).

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The Scientific World Journal
Volume 2012, Article ID 835917, 9 pages
doi:10.1100/2012/835917

Research Article

An Assessment of Japanese Carbon Tax Reform Using the E3MG Econometric Model

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Received 24 September 2012; Accepted 10 October 2012

Academic Editors: B. Chen, Z.-M. Chen, and H.-S. Tang

This paper analyses the potential economic and environmental effects of carbon taxation in Japan using the E3MG model, a global macroeconometric model constructed by the University of Cambridge and Cambridge Econometrics. The paper approaches the issues by considering first the impacts of the carbon tax in Japan introduced in 2012 and then the measures necessary to reduce Japan's emissions in line with its Copenhagen pledge of −25% compared to 1990 levels. The results from the model suggest that FY2012 Tax Reform has only a small impact on emission levels and no significant impact on GDP and employment. The potential costs of reducing emissions to meet the 25% reduction target for 2020 are quite modest, but noticeable. GDP falls by around 1.2% compared to the baseline and employment by 0.4% compared to the baseline. But this could be offset, with some potential economic benefits, if revenues are recycled efficiently. This paper considers two revenue recycling scenarios. The most positive outcome is if revenues are used both to reduce income tax rates and to increase investment in energy efficiency. This paper shows there could be double dividend effects, if Carbon Tax Reform is properly designed.

1. Introduction

In recent years, the Japanese Government has proposed to introduce low-carbon policy instruments such as a carbon tax and ETS by introducing the bill of the Basic Act on Global Warming Countermeasures in 2009. The carbon tax plan was approved at the cabinet meeting in December 2011 (instead of ETS) due to strong ETS opposition from business circles. The bill has now been passed by the Japanese diet (March, 2012), making the carbon tax the first one to be introduced in Asia. The effects of carbon taxes on GHG emissions and the wider economy are now attracting the notice of many researchers and policy makers in this area.

The aim of this paper is to analyse the potential economic and environmental effects of implementing low-carbon policies, notably carbon taxation, in Japan. The analysis provides an input to the discussion by presenting a quantitative assessment of carbon taxation in Japan. The approach is model based and uses E3MG, a global macroeconometric model that links the world's economies to their energy systems and associated emissions. The assessment approaches the issue from two angles by considering first the impacts of the tax increases put forward in 2010 and then the measures that would be needed to reduce Japan's emissions in line with its Copenhagen pledge of −25% compared to 1990 levels.

This analysis builds on previous work by, among others, Park [1], Kawase et al. [2], and Takeda [3], who examined the effects of ETR using CGE (Computable General Equilibrium) models. E3MG shares many of the features of such models, for example, GTAP [4], the Monash model, and GEM-E3 [5], but relaxes some of the common assumptions to the CGE approach (such as fully rational behaviour), instead using an empirical approach (see Section 3). The structure of E3MG makes it more similar to the approach used in Sugawara [6], but E3MG is much larger in scale and with a much larger disaggregation of sectors.

The paper is structured as follows: Section 2 summarises the policy environment in Japan that provides the basis for this analysis; Section 3 describes the E3MG model, while Sections 4 and 5 describe the scenarios that were assessed and the results from these scenarios, respectively; Section 6 concludes.

2. Background: Japanese Climate Change Policy

2.1. A Brief Description of Japanese Climate Change Policy. Japan has been pushing for the adoption of measures to combat climate change since 1997, just after the agreement of Kyoto Protocol. The Law Concerning the Promotion of the Measures to Cope with Global Warming, for example, became effective in 1998. However, this law required business circles and householders to try to reduce GHG emissions without any imperative policy instruments like carbon taxes or ETS. Emission reduction efforts from business have depended on the Voluntary Action Plan led by Keidanren (Keidanren is the most influential general business association in Japan to which 1,281 leading companies and 127 industrial associations belong). Reductions from households have depended on government-led campaigns such as Cool Business, which requests people to control their office and room air conditioner over 28°C with light dress (e.g., no necktie and no jacket, etc.) during the summer season.

In 2009, the Japanese Government submitted the bill of the Basic Act on Global Warming Countermeasures to parliament. The bill outlined a mid-term goal to reduce GHG emissions by 25% below the 1990 level in 2020 and a long-term goal of 80% below the 1990 level in 2050. Further goals include raising the share of renewable energy within total primary energy supply to 10% by 2020. Measures to achieve these targets have included proposals for carbon taxes and also an emissions trading scheme (ETS). The Committee on Institutional Design for Emissions Trading was established in 2000 by the Environmental Agency and began examining the introduction of an ETS at national level. The committee investigated an ETS as a domestic measure to achieve Japan's greenhouse gas reduction target under the Kyoto Protocol (see Committee on Institutional Design for Emissions Trading [7]).

In 2010, the Ministry of the Environment in Japan proposed an ETS that would be implemented in 2013. However, despite strong requests to implement an ETS from environmental NGOs and academia, the ruling party (i.e., the Democratic Party of Japan) proposed a postponement of its implementation on December 17, 2010, due to opposition from Keidanren and industry as well as potential negative economic impacts (advocates for the implementation of a cap-and-trade ETS include the Kiko Network [8], an environmental NGO, and Morotomi and Ayukawa [9]). At the end of 2010, the Japanese government opted to introduce a carbon tax in 2011 instead of an ETS. However, the implementation of this tax was put off until 2012 by the influence of the 2011 tsunami in Japan.

Nevertheless, from the perspective of promoting global warming mitigation measures and pushing for energy conservation after the 2011 tsunami, there was a determined push in Japan to introduce a carbon tax (Special Provisions for Carbon Dioxide Tax of Global Warming Measures), and the Japanese FY2012 Tax Reform Revision passed the House of Councilors on March 30, 2012. It will be implemented from October 1, 2012. As a result, the government will increase the rates, depending on carbon content, of the present Petroleum and Coal Tax, which is imposed on all fossil fuels.

Table 1: FY2012 proposed tax rates.

	Crude petroleum/petroleum products (per kilo liter)	Gaseous hydrocarbon (per ton)	Coal (per ton)
Present	JPY 2,040	JPY 1,080	JPY 700
October 1, 2012	JPY 2,290	JPY 1,340	JPY 920
April 1, 2014	JPY 2,540	JPY 1,600	JPY 1,140
April 1, 2016	JPY 2,800	JPY 1,860	JPY 1,370

The first scenario in this paper simulates the potential effects of FY2012 Tax Reform.

2.2. Carbon Tax Plan Details. The FY2012 Tax Reform (see http://www.mof.go.jp/english/tax_policy/tax_reform/fy2012/tax2012a.pdf) specifies that the Japanese Government will introduce a Carbon Dioxide Tax with the aim of controlling energy-originated CO_2 emissions, which currently account for around 90% of GHG emissions.

The government will add the following tax rates, corresponding to the amount of CO_2 emissions, to existing fossil fuel prices (including existing taxes):

(i) crude oil, petroleum products: JPY 760/kl,

(ii) gaseous hydrocarbons: JPY 780/t,

(iii) coal: JPY 670/t.

The additional taxes are set to be introduced, in part, on October 1, 2012 and increased progressively such that they are fully implemented by 2016. Table 1 specifies the interim measures in further detail. These figures are used to define the first scenario in this paper.

3. The E3MG Model

This section briefly describes the E3MG model that was used to carry out the analysis. For further information about the model, the reader is referred to Barker et al. [10] and the website http://www.e3mgmodel.com

3.1. Basic Model Structure. The E3MG model (energy-environment-economy model at the global level) is a computer-based tool that has been constructed by international teams at the University of Cambridge and Cambridge Econometrics. The model is econometric in design and is capable of addressing issues that link developments and policies in the areas of energy, the environment, and the economy. The essential purpose of the model is to provide a framework for policy evaluation, particularly policies aimed at achieving sustainable energy use over the long term. However, the econometric specification that the model uses also allows for an assessment of short-term transition effects.

The current version of E3MG consists of 22 world regions, although in this analysis we focus solely on Japan. The basic structure of E3MG is presented in Figure 1. The model integrates energy demand and emissions with the economy; fuel demand is determined by prices and economic activity with feedback through the energy supply sectors. Energy combustion results in greenhouse gas emissions.

The economic module in E3MG contains a full representation of the National Accounts, as formulated in Cambridge by Richard Stone, and formally presented in European Communities et al. [11]. A key feature of E3MG is its sectoral disaggregation, with 42 economic sectors, linked by input-output relationships; this aspect is particularly important in modelling carbon taxes as the different sectors use different fuels in varying degrees of intensity and have different technological options for changing consumption patterns.

Exogenous inputs to the model include population, government tax and spending rates, and international energy prices. The outputs include a range of economic and labour market indicators, defined at sectoral level, plus indicators for energy consumption and emissions.

Figure 2 shows the mechanism through which a carbon tax could affect macroeconomic outcomes. The taxes are levied on consumption of fuel use, leading to reductions in fuel demand but also higher costs for industries and households. Higher industry costs may be absorbed as loss of profits or passed on to final consumers. Higher prices mean losses of real output for domestic consumers and for exporters.

However, the revenues from carbon taxes may also be used to reduce other tax rates, with positive economic benefits. In the scenarios in this paper, a large share is used to reduce income taxes. The effects this has on the economy are shown in Figure 3; reduced income taxes lead to higher incomes, which are spent on consumer goods and lead to increases in domestic production, creation of jobs, and further income rises (i.e., a multiplier effect).

E3MG's treatment of energy demand is largely top-down in nature. Econometric equations are estimated for aggregate energy demand and demand for the four main fuel types (coal, fuel oil, natural gas, electricity). Energy demand, for 19 different user groups, is a function of economic activity, relative prices, and measures of technology. The model solves all equations simultaneously and adjusts the individual fuels to sum to the total for each user. Feedbacks to the economy are provided by adjusting input-output coefficients and household energy demand.

The following equations provide an example of E3MG's econometric, error-correction equations for aggregate energy consumption (*EnCon*) at time t. First a long-run equation is estimated based on levels of economic activity (*Act*), energy prices (*EnPrice*), investment (*Inv*), and *R&D*. The lagged errors from this equation (e) are then used in the short-run equation which uses differences of the same independent variables, plus the lagged dependent variable.

Long Run:

$$\begin{aligned} EnCon_t = {} & a_1 + (b_1 * Act_t) + (b_2 * EnPrice_t) \\ & + (b_3 * Inv_t) + (b_4 * R\&D_t) + e_t. \end{aligned} \tag{1}$$

Short Run:

$$\begin{aligned} \Delta EnCon_t = {} & a_2 + (b_1 * \Delta Act_t) + (b_2 * \Delta EnPrice_t) \\ & + (b_3 * \Delta Inv_t) + (b_4 * \Delta R\&D_t) + (b_5 * e_{t-1}) \\ & + (b_6 * \Delta EnCon_{t-1}) + \in_t. \end{aligned} \tag{2}$$

The exception to this top-down treatment is in power generation, as the historical data do not provide the basis to estimate econometric equations in new technologies. In this sector E3MG includes a bottom-up representation with 28 specific generation technologies, made up of both conventional and renewable supplies. The model bases future investments on the relative prices of each technology, including the effects of carbon taxation. This part of the model is described in Barker et al. [12].

Emissions are estimated using a fixed coefficient to fuel demand. Nonenergy emissions are included in the model so that global totals are met but are treated as exogenous in this paper.

E3MG also includes endogenous measures of sectoral technological progress. The indices used in the model are functions of accumulated capital, enhanced by R&D, adapted from Lee et al. [13]. Endogenous technological progress is allowed to influence several of the model's equation sets, including energy demand, international trade, price formation, and the labour market.

3.2. Data Sources and Equation Estimation. As an econometric model with sectoral detail, E3MG requires extensive data inputs. A large time-series database covering 1970–2008 annually (with more recent aggregate figures where available) has been constructed, in the main based on international datasets. For Japan the main data source for economic data is the OECD Structural Analysis database, with other macro-level indicators being obtained from the IMF and the World Bank. If there are gaps in the data these are filled using national figures. The main cross-sectional data (the input-output table and bilateral trade flows) are sourced from the OECD.

The main source for energy data is the IEA. CO_2 emissions have also been made consistent with IEA figures.

E3MG consists of 22 estimated sets of equations (each disaggregated by sector and by country). These cover the components of GDP, prices, the labour market, and energy demand.

The estimation method utilises developments in time-series econometrics, in which dynamic relationships are specified in terms of error correction models (ECM) that allow dynamic convergence to a long-term outcome.

The specific functional form of the equations is based on the econometric techniques of cointegration and error-correction, particularly as promoted by Engle and Granger

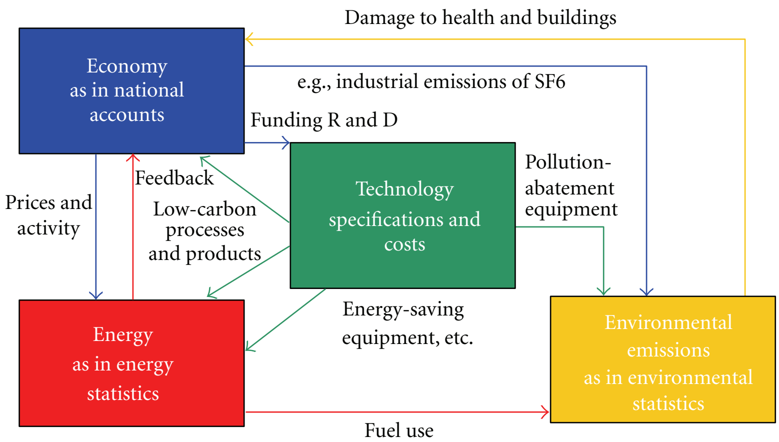


Figure 1: E3 interactions within E3MG.

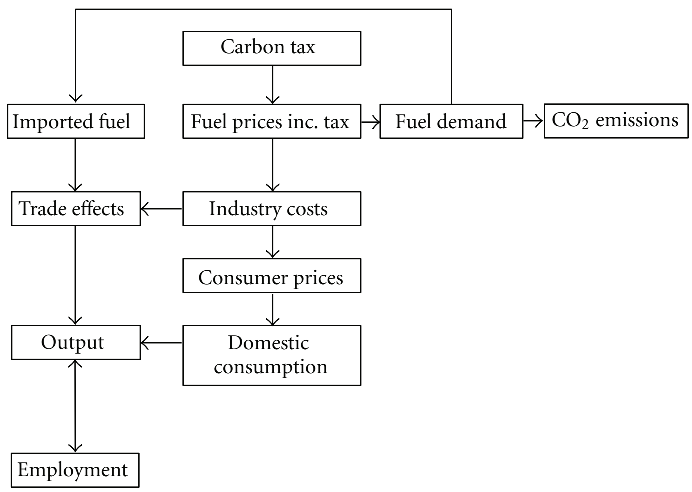


Figure 2: Potential effects of a carbon tax.

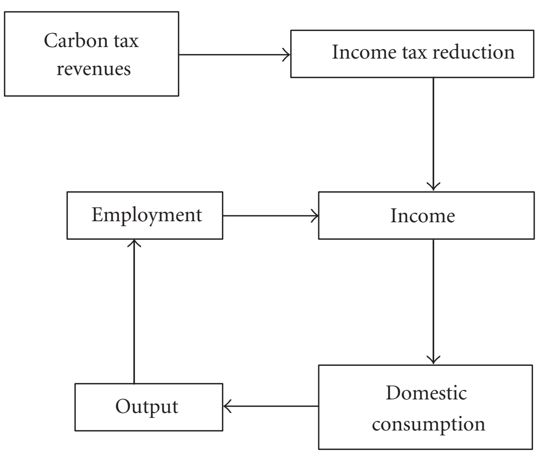


Figure 3: Potential effects of revenue recycling.

[14] and Hendry et al. [15]. In brief, the process involves two stages. The first-stage is a levels relationship, whereby an attempt is made to identify the existence of a cointegrating relationship between the chosen variables, selected on the basis of economic theory and a priori reasoning. For example, for employment demand the list of variables contains real output, real wage costs, hours worked, energy prices, and a measure of technological progress. If a cointegrating relationship exists, then the second stage regression is known as the error-correction representation and involves a dynamic, first-difference, regression of all the variables from the first stage, along with the lagged difference in the dependent variable, and the error-correction term (the lagged residual from the first stage regression).

3.3. Previous Analysis with E3MG. The E3MG model has been under development for much of the past decade. It is now used for policy analysis at European level, including the 2010 European Commission communication on the impacts of moving to a 30% GHG target. The model has also been used repeatedly for assessing decarbonisation pathways at different international levels [10] and in the UK [16]. Most recently E3MG was applied in Barker et al. [17] to provide an economic assessment of the IEA's 450 ppm scenario [18].

Also of potential application to these scenarios and their underlying policy context is the model's assessment of rebound effects [23]. In this paper the E3MG model was used to show that long-run rebound effects can cancel out up to 50% of the environmental gains from efficiency measures; the analysis goes on to recommend carbon pricing as a means to reduce the rebound effect.

3.4. Comparison to CGE Modelling. In terms of basic structure, purpose, and coverage, there are many similarities between E3MG and comparable CGE models, such as GTAP [4], the Monash model, and GEM-E3 [5]. Each is a computer-based economic model that considers energy-environment-economy interactions at the global level, broken down into sectors and world regions. In addition the regional and sectoral disaggregations are broadly similar. Both modelling approaches are based on a consistent national accounting framework and make use of similar national accounts data.

However, beneath the surface there are substantial differences in modelling approach and it is important for the reader to be aware of this when interpreting results. The two types of model come from distinct economic backgrounds. While the models are quite consistent in their accounting, identity balances, they differ substantially in their treatment of unobservable behavioural relationships. The CGE model favours setting these in line with economic theory, for example, by assuming that individuals act rationally in their own self-interest. In contrast, the econometric model interrogates historical datasets to try to determine these factors on an empirical basis.

Both approaches have their relative strengths and weaknesses; for example, the assumption of optimising rational behaviour in CGE models has been increasingly questioned since the recession, while econometric models are reliant on having high-quality time-series data. Although subtle, these differences in theoretical approach can lead to different conclusions being drawn from the model results; for example, the econometric model does not assume optimal behaviour in the baseline, implying that negative-cost emission reductions are available. Jansen and Klaassen [24] and Bosetti et al. [25] describe some of the differences in the context of ETR, including revenue recycling options.

This distinction is important when comparing the analysis in this paper to previous model-based assessments in Japan, which have almost exclusively used a CGE approach, as discussed in Section 1. In Europe it is now common for CGE and macroeconometric models to be run in tandem so that results are not dependent on a single set of modelling assumptions (e.g., [19]).

4. Scenarios

4.1. Baseline. The baseline that has been used for this analysis has been scaled to be consistent with the current policies scenario in *World Energy Outlook*, 2010 ([18], henceforth referred to as WEO). E3MG's equation results are set to match WEO figures for energy demand and emissions, but also to use the same figures for economic drivers in order to retain consistency throughout the model's internal relationships. In summary, by 2020,

(i) total energy-related CO_2 emissions are expected to fall to 998 $mtCO_2$, from 1,147 $mtCO_2$ in 2008 and 1,063 in 1990;

(ii) total primary energy demand is expected to be stable at current levels;

(iii) final consumption of oil is expected to slowly decrease, but consumption of electricity to increase;

(iv) additional electricity will be generated from nuclear power.

The 2010 edition of WEO does not include the latest data regarding the recession or the impacts of the Fukushima nuclear accident (which clearly raises questions on the suitability of the final bullet point) but, while this may impact on the magnitude of results, in our view it does not change the direction of results, or the overall conclusions from this paper. Nevertheless, one of our recommendations is to repeat this exercise once there is more certainty about the global economy and Japanese energy and climate policy.

4.2. Policy Scenarios. We consider four policy scenarios. The first scenario assesses the economic and environmental impacts of the tax increases that were announced for FY2012. The other scenarios consider the measures that would be necessary to reduce GHG emissions by 25% from 1990 levels, in line with Japan's Copenhagen pledge. There are three variants of this scenario, one with the carbon tax levied on its own and two options with different methods of revenue recycling (where revenues from carbon taxes are used to reduce revenues from other taxes). In scenario 2b, some of the revenues are used to fund a public investment programme in energy efficiency (the investment in energy efficiency is assumed to lead to reductions in energy demand using the ratios of investment and energy savings for OECD countries published in IEA [18]) in buildings, while in S2c they are used to reduce labour costs.

The scenarios are summarised in Table 2, while Table 3 illustrates the tax inputs for each scenario. Inputs for S2a, S2b, and S2c are not derived from Japanese policy but are estimated by E3MG based on achieving the CO_2 emissions reduction target of 25% in 2020 compared to 1990.

5. Results

5.1. Environmental Impacts. Figure 4 shows the impact on energy-related CO_2 emissions, compared to baseline, in each of the scenarios.

The first result is that the FY2012 measures that are modelled in S1 have only a small impact on emissions levels; this is because their impact on fuel prices (i.e., the relative effect once the taxes are added to fuel costs and existing taxes) is very small, in the range of 1–3%. This provides little incentive for behavioural change, and there are only small reductions in fuel consumption. In the other scenarios, emissions fall by slightly more than 20% compared to baseline (which is 25% below 1990 levels). However, quite

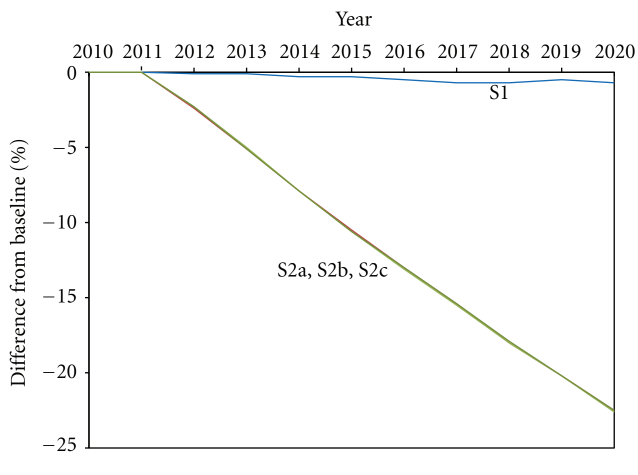
Table 2: Summary of scenarios.

	Carbon tax rates	Revenue recycling
S1	FY2012 reform	None
S2a	To reach 25% GHG reduction	None
S2b	To reach 25% GHG reduction	95% of revenues used to reduce income taxes, 5% used for investment in energy efficiency
S2c	To reach 25% GHG reduction	75% of revenues used to reduce income taxes, 25% used to reduce employers' social security contributions

Table 3: E3MG carbon tax inputs (JPY/toe).

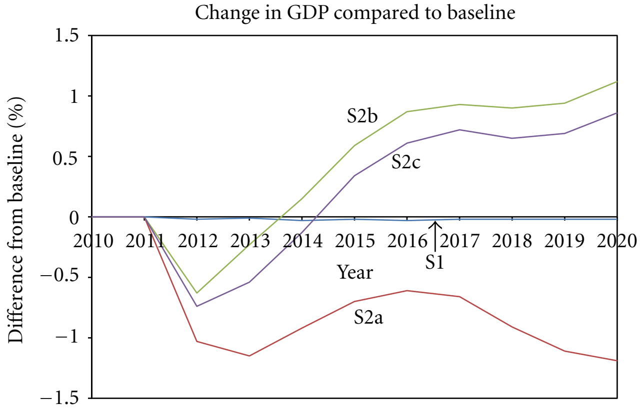
	S1			S2a	S2b	S2c
	Oil	Gas	Coal	All fuel types		
2012	325	305	371	17,721	20,529	19,812
2013	325	305	371	26,982	25,843	29,316
2014	651	610	743	29,508	29,215	32,487
2015	651	610	743	30,709	28,652	32,468
2016	989	915	1,131	32,500	27,460	33,318
2017	989	915	1,131	35,257	28,750	35,868
2018	989	915	1,131	39,749	33,140	41,531
2019	989	915	1,131	43,192	36,528	45,426
2020	989	915	1,131	44,240	35,615	45,811

Notes: Figures based on 1 USD = 76.8 JPY.
S1 values derived from FY2012 tax rates.
S2 values required to achieve 25% reduction in CO_2 emissions between 1990 and 2020.
Source(s): E3MG, Cambridge Econometrics.



Source(s): E3MG, Cambridge Econometrics

Figure 4: Energy-based CO_2 emissions, Japan.



Source(s): E3MG, Cambridge Econometrics

Figure 5: Japan GDP.

a high carbon price is required to do this in such a short period of time; the model results suggest that electricity prices would need to increase by up to 50% and motor fuel prices increase by around 40%.

5.2. Macroeconomic Impacts. Our results suggest that the average annual revenues raised during 2012–2020 would be approximately ¥310 bn ($4 bn) in S1 and ¥11,500 bn ($150 bn) per year in the variants of S2. The latter equates to around 3% of GDP and is clearly enough to have an impact on macroeconomic indicators.

Previous model-based studies, including Andersen and Ekins [26] and Ekins and Speck [27], have found that it is possible to reduce CO_2 emissions while simultaneously increasing GDP through carefully designed ETR. The results in this paper are consistent with this finding, on the condition that the revenues generated by carbon taxes are recycled effectively. As Figure 5 shows, modest GDP gains of up to 1.2% in 2020 (compared to baseline) are possible under these scenarios. It is also notable that the potential costs to GDP in S2a are also quite small.

The reason that GDP increases in the scenarios with revenue recycling is that the positive effects of reducing income taxes outweigh the negative effects of higher energy costs. The recycled revenues (including the share allocated to investment or reducing social security contributions) sum to the revenues from the carbon taxes, so the same amount of demand is in the system. However, there is a reallocation within the system that produces economic benefits for two main reasons.

(i) As Japan imports such a large share of its energy, any measures that reduce energy consumption are likely to boost the trade balance and hence GDP.

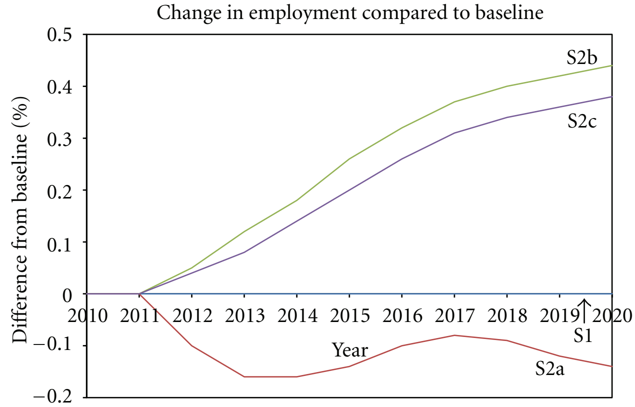
(ii) Much of the higher energy costs fall on business which may not pass these costs on to final consumers (e.g., due to international competition); there is therefore a redistribution from companies (lower profits) to workers (higher incomes), but workers have a lower savings ratio meaning there is additional spending overall.

The second of these effects is dependent on cost pass-through rates which are largely determined by econometric estimates. Our results suggest that pass-through rates in

Table 4: Macroeconomic impacts, Japan.

	S1	S2a	S2b	S2c
GDP	0.0	−1.2	1.1	0.9
Employment	0.0	−0.1	0.4	0.4
H'hold consumption	0.0	−1.6	2.0	1.7
Investment	0.0	−0.6	0.9	0.7
Exports	0.0	−0.5	−0.4	−0.5
Imports	0.0	−0.3	1.1	1.1
Price level	0.1	2.5	1.4	2.0

Values are % difference from the Baseline.
Source(s): E3MG, Cambridge Econometrics.



Source(s): E3MG, Cambridge Econometrics

Figure 6: Japan employment.

Japan are often low, which contributes to the GDP benefits. (The reasons for this are not clear but could be linked to the period of deflation. To test the impact of this we carried out a sensitivity analysis with 100% pass-through, as is common in CGE models. The results showed that GDP still increased in scenarios 2b and 2c but by less than the amount reported in this paper.) Table 4 shows the impacts on the price level and other macroeconomic indicators.

Another reason that the measures with revenue recycling have a positive impact on GDP is the fact that Japan is relatively less exposed to international trade. This means that the competitiveness effects of carbon taxes (higher domestic costs leading to higher imports and lower exports) are less, while the impacts of the revenue recycling are higher (consumers spend less of the extra income on imports). This means that, despite a worsening trade balance, increases in household expenditure lead to quite positive results to GDP overall.

Impacts on investment are quite small, except when a share of the revenues is used to fund investment programmes. The impacts on employment are smaller in scale than the impacts on GDP (see Figure 6) but generally follow the same pattern. In S2c additional jobs are created as a result of a share of the revenues being used to reduce labour costs.

Additionally, the model results enable us to compare the macroeconomic effects between different approaches to revenue recycling. The revenue recycling scenarios both cause GDP and employment to increase in comparison to the scenario without revenue recycling (S2a). S2b, which considers using revenues to both reduce income tax and increase investment in energy efficiency, has slightly greater positive effects than S2c, which also uses revenues to reduce income tax but combined with reducing employers' social security contributions.

Our model results are consistent with the "double dividend hypothesis." (This is explained in Goulder [28].) Apart from increasing welfare due to lower pollution externalities (a green dividend), environmental taxes raise revenue that can be used to lower other pre-existing tax distortions, resulting in economic welfare gains from a smaller deadweight loss of the tax system, or "efficiency" dividend.

5.3. Sectoral Impacts. As with any new policy there will be winners and losers created. Table 5 summarises the main sectoral impacts from the model results in terms of changes in real output. It is important to note that the level of sectoral detail in the model is limited by the available data and that there will be subsectors and specific firms that will be affected by more than the sectoral figures shown here.

The patterns in outcomes are as would be expected from such a modelling exercise. The energy sectors suffer a loss in demand from their output, although much of this is met by lower imports. Electricity sees the greatest reduction in output in all of the scenarios. Other sectors that stand to lose out are those that are intensive users of energy and are exposed to international competition.

The sectors that stand to benefit are typically those that are not carbon intensive and supply products to consumers (see Table 5). Within S2a, some consumer sectors, such as hotels and catering, benefit from a shift in spending away from energy, but the overall outlook is negative. As household incomes increase in S2b and S2c, the same sectors benefit from additional spending that is directed towards them. In addition, the investment sectors benefit in S2b as a result of the spending programme. Output in textiles and clothing is quite sensitive, with strong negative effects in S2a but notable positive effects in S2b and S2c. This suggests a high income elasticity of demand in the sector.

The patterns for sectoral employment are similar to the ones for sectoral output. Figure 7 also illustrates a more detailed time-series representation of the most positively and negatively affected sectors in S2a.

5.4. Comparison to Previous Results in Japan. While the modelling results are consistent to similar exercises carried out in Europe using a similar modelling approach (e.g., [26]), they should also be compared to previous analysis carried out in Japan.

In Japan, the CGE model has been the main tool to analyse the economic and environmental effects of carbon taxes. Using a CGE model, Park [1] shows double dividend effects of a carbon tax for a 20% emission reduction target in 2010, using the revenues to cut employers' social contributions (as has been done in S2c). This carbon tax

Table 5: Real output effects, selected sectors.

S1		S2a		S2b and S2c	(S2b)	(S2c)
Gas supply	−0.3	Basic metals	−2.0	Printing and publishing	6.1	5.6
Electricity	−1.0	Textiles and clothing	−2.6	Hotels and catering	5.3	5.1
		Gas supply	−6.6	Food/drink and tobacco	5.3	4.8
		Electricity	−28.5	Textiles and clothing	4.8	4.1

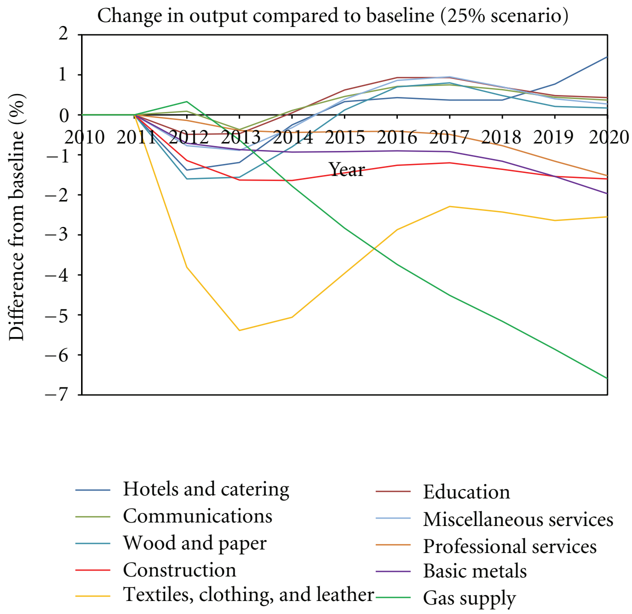
Notes: values are percent of difference from the baseline.
Source(s): E3MG, Cambridge Econometrics.

scenario resulted in a GDP increase between 0.16 and 0.49% in 2010 compared to baseline. Also based on CGE modelling, Park [29] introduces a 30,000 yen/tCO_2 carbon tax to achieve the Japanese Kyoto Protocol target of 6% GHG reductions in 2010 compared to 1990. The results show double dividend effects for a carbon tax with revenue recycling.

Kawase et al. [2] analysed the effects of a 3,000 yen/tCO_2 carbon tax using CGE and industrial I-O analysis. The results showed a reduction in CO_2 between 0.11 and 0.27% and an increase in GDP between 0.01 and 0.09% compared to baseline, with the revenues recycled through cuts in consumption or income taxes.

Sugawara [6] suggested that Japanese GDP will increase by 1-2% annually without introducing low-carbon policy. But, based on analysis using a macroeconometric model, this would be reduced to zero (and the unemployment rate would increase by 3 percentage points) if Japan introduced a carbon tax to meet its 25% GHG 2020 target. However, if the tax revenues are recycled to public investment, the negative impacts would be lessened.

For the main part, the studies above show results that are consistent with the analysis presented in this paper. A carbon tax with revenue recycling could have a positive impact on GDP and seems very likely to lead to reduced CO_2 emissions. But the results for achieving a 25% reduction target in this paper suggest a larger economic effect than previous studies. This partly reflects the structure of the E3MG model, with many of the assumptions that are common to CGE models being relaxed. However, it also reflects the ambitious nature of the 25% reduction target, high international energy prices (meaning that reductions in imported fuels have greater economic benefit), and the spare economic capacity that is available in the Japanese and global economies following the financial and economic crisis.



Note(s): values are based on the 5 most positively and negatively affected sectors in S2a
The graph does not include the electricity sector (−28.5% in 2020)
Source(s): E3MG, Cambridge Econometrics

Figure 7: Selected output effects under 25% reduction target.

6. Conclusions

This paper analyses the effects of carbon taxes on GHG emissions and the wider economy for the Japanese FY2012 Tax Reform Revision. It also includes three scenarios of carbon taxes that are simulated to reduce GHG emissions by 25% in 2020 compared to 1990 levels. The analysis uses the E3MG model developed by the University of Cambridge and Cambridge Econometrics.

The results from the model suggest that the FY2012 Tax Reform Revision has only a small impact on emission levels and no significant impact on GDP and employment.

The potential costs of reducing emissions by a large percentage (to meet the Copenhagen target for 2020) are quite modest, but noticeable (GDP falls by around 1.2% compared to baseline and employment by 0.4% compared to baseline). But this could be offset, possibly with some economic benefits, if revenues are recycled efficiently. The results suggest that there could be double dividend effects, if the revenues from carbon taxes are recycled efficiently.

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The Scientific World Journal
Volume 2012, Article ID 917830, 9 pages
doi:10.1100/2012/917830

The ScientificWorldJOURNAL

Research Article

Life-Cycle-Based Multicriteria Sustainability Evaluation of Industrial Parks: A Case Study in China

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Received 7 September 2012; Accepted 22 November 2012

Academic Editors: D. F. Cheddie, H. Choi, and N. Özbay

Along with increasing concerns on environmental protection and global warming mitigation, new industrial organization modes such as "Ecoindustrial Park" and "Low Carbon Industrial Park" are emerging. Since ecoindustrial parks and low carbon industrial parks may offer multifaceted benefits to the users, it naturally follows that the sustainability assessment of the industrial parks ought to adopt a multicriteria methodology. In this paper, a multicriteria sustainable evaluation framework is proposed in combination with the life cycle analysis and applied to a low carbon and high end industrial park (LCHE) in Beijing, China. Results show that the LCHE industrial park can contribute to both energy-saving and greenhouse gas emission mitigations compared with other industrial parks. In terms of economic performance, although the economic profits are considerable, the investment per constructed area is relatively high. The results of sustainable analysis of the LCHE industrial park can thus shed light on future upgrading of industrial parks.

1. Introduction

Industrial parks are defined as the land areas developed and subdivided into plots according to their integrated plans with provisions for roads, transport, and public utilities for the use of a group of industrialists [1]. Industrial parks usually function as small cities with complete infrastructural facilities, intermaterial and information flows, and semi-artificial environmental conditions. They assimilate materials from the outside and deliver products to the human society. As a cardinal unit of economic development, industrial parks have been playing an important role in the national development strategies of many countries and have been irreplaceable where economic development is concerned [2]. There are several interchangeable terms for industrial parks, which often vary depending on the scope and type of operations, for example, business parks, office parks, science and research parks, hi-tech centers, and bio-technology parks [3]. As many industrial types exist, it opens up an opportunity to establish the most sustainable or ecoefficient industrial park.

Considering the coordination of economic development and environmental protection, the concept of "Eco-industrial Park" (EIP) was proposed and defined as "a community of manufacturing and service businesses located together on a common property." Member businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of individual benefits each company would realize by only optimizing its individual performance [4–7]. In China, accelerated by the "National Pilot EIP Program" and "National Pilot Circular Economy Zone Program," 60 industrial parks have received approval to be developed into national pilot EIPs [8].

The world is experiencing a behavior transition triggered by climate change in recent years. To probe into the status and trend of global warming, research has been widely conducted focusing on complex social-economic systems [9–15]. With the concurrent concerns on climate change, the construction of low carbon industrial parks is emphasized to favor the development of low carbon economy in China. Low carbon industrial park is an updated EIP with carbon emission control taken into consideration. The establishment of low carbon industrial park aims at minimizing the carbon emissions and environmental impacts while maximizing the economic output. It involves low carbon building, low carbon lifestyle, preferable environment, and high economic efficiency. Now, some pilot low carbon industrial parks have already been established in China, for example, the Shanghai Expo Area.

Although the construction of EIPs or low carbon industrial parks is quite popular, the sustainability assessment of industrial parks is a topic that has not been well documented. It appears that most sustainability studies on industrial parks fail to link the infrastructure developments to the energy system thus focusing more on limited aspects such as direct energy consumption [16], environmental impacts [17], economic or social performance [18], or inner metabolism [19].

Since EIP and low carbon industrial park may offer multifaceted benefits to the users, it naturally follows that any sustainability assessment of the industrial park ought to adopt a multi criteria methodology. Hence, sustainability assessment of industrial parks should be illustrated considering the dimensions of environmental, economic, resource sustainability. Based on the concept of life cycle analysis (LCA), which is commonly used to trace the energy consumption and carbon emissions of artificial ecosystems [20–25], especially buildings [26–30], this paper aims to propose a sustainability evaluation framework which integrates the environmental impacts, economic output, and resource depletion and apply it to a low-carbon and high-end (LCHE) industrial park in China. The remainder is organized as follows: Section 2 describes the evaluation framework, that is, the environmental, economic, and resource depletion evaluation indicators. In Section 3, the case concerned is introduced. The accounting results are integrated and demonstrated in Section 4. Finally, Section 5 presents the conclusions of this paper.

2. Methodology

The general requirements for selection of impact criteria are reliability, measurability, and relevance/usefulness [31]. Based on these disciplines and the LCA framework, an outline is proposed to evaluate the sustainability (including environmental, economic, and resource performance) of the industrial parks. After clarifying the objective and system boundary, an inventory analysis is performed firstly in terms of the total material inputs. Then, the calculated environmental emission, economic investment, and resource consumption are demonstrated, based on which a set of indicators are finally calculated. Thus, a LCA based multi criteria sustainability evaluation framework is established. The proposed indicators are listed in Table 1.

2.1. Environmental Evaluation. As climate change is attracting more and more public concerns, greenhouse gas emission is selected to represent the environmental impact of industrial parks in this sustainability evaluation framework. Both carbon sources and sinks are considered in the construction stage using indicators of carbon emission density and the greening rate, which can be viewed as the pillars of an environmental managerial decision. Specifically, greenhouse gas emission intensity, which is a measurement of environmental impact in the operation phase, entails the environmental cost of economic development. The higher the greenhouse gas emission intensity, the larger pressure exerted on climate change and environmental mitigation. In the dismantling phase, greenhouse gas emission removal rate is used to quantify the role of material recycling in mitigating greenhouse gas emission.

2.2. Economic Evaluation. The economic sustainability dimension includes aspects directly and indirectly quantifiable in monetary terms such as, respectively, total investment per area, and economic output per area, which are reflections of costs and economic vigor of industrial parks [31]. The computations of economic indicators are also based on the life cycle concept, including economic inputs per constructed area on building works and infrastructure installation and the economic output per area in the operation stage of industrial parks.

2.3. Resource Depletion. The resource depletion in the construction phase is illustrated by two indicators, that is, energy density and water recycling rate. Energy density is defined as the embodied energy consumption per construction area. It is a criterion for energy performance comparison among different industrial parks. As waste water is treated and reused through a waste water treatment system in most industrial parks, the water recycling rate is employed to measure the renewability of industrial parks. In the operation stage, Energy intensity, which is specified as the energy consumption per $, is employed to demonstrate the energy cost along with economic development. It also functions as a goal-function for tradeoffs between energy saving and economic development. Energy saved by material recycling in the dismantling stage is also signified by the indicator of energy reduction rate.

3. Case Study

3.1. Description of Study Site. The concerned LCHE industrial park is located in the northeast of Beijing, China. There is a convenient transportation network with Jinghu national highway, light rail Yizhuang line, the Fifth Ring Road, and other thoroughfares connected to this area. In this industrial park, totally 159 enterprises, covering high-end economies such as intelligent, innovative, and design ones, are concentrated. Capital investments of settled enterprises in this industrial park amount to $82.53 billion, and more than 5000 employments are provided.

The industrial park has a floor space of 0.174 million square meters and built up area of 0.336 million square meters. It is divided into Zone A and Zone B. Zone B with 43 office buildings (3-4 floor building) is studied in this paper. As shown in Figure 1, the concerned Zone B consists of settled enterprises, property services, and the supporting

Table 1: Sustainability evaluation indicators in the multicriteria scheme.

Categories	Stages	Indicators	Units	Explanation
Environmental	Construction	Greenhouse gas emission density	kg CO_2 eq/m^2	The greenhouse gas emission in the construction phase divided by construction area.
		The greening rate	%	The proportion of green land to the total construction area of industrial parks.
	Operation	Greenhouse gas emission intensity	kg CO_2 eq/$	The greenhouse gas emission in the operation phase divided by economic output.
	Dismantling	Greenhouse gas emission removal rate	%	The greenhouse gas emission avoided by material recycling divided by total greenhouse gas emission in the construction and operation stages.
Resource	Construction	Energy density	J/m^2	Energy consumption per construction area in the construction phase.
	Operation	Water recycling rate	%	The proportion of reused water to total water consumption.
		Energy intensity	J/$	Energy consumption per economic output in the operation phase.
	Dismantling	Energy reduction rate	%	Energy recycled in the dismantling phase divided by total embodied energy consumption.
Economic	Construction	Investment per area	$/m^2	All expenses that support the construction of the industrial parks per built-up area.
	Operation	Economic output per area	$/m^2	Economic output produced by settled enterprises per m^2.

environment of the industrial parks. A rainwater collection system and a waste water treatment system are installed as auxiliary engineering. The plot ratio of buildings is 0.77 and the building intensity is 31.62%.

3.2. Goal and Scope. The study presented in this paper uses an LCA framework as a tool to conduct the sustainability evaluation of a LCHE industrial park in Beijing, China. An inventory of the materials involved in the construction, operation, and dismantling stages is used to calculate the environmental, economic, and resource conditions. The goal of the study is to investigate the economic performance, environmental consequences, and resource depletion of the industrial park and identify if the so-called low carbon industry is more sustainable than other industrial estates.

3.3. System Boundary. All material and facility inputs in the lifetime (construction, operation, and dismantling phases) of the industrial park are accounted. In the construction phase, 12 subsystems are accounted including ventilation and air conditioning system, municipal water supply and drainage system, architectural electrical engineering, building water supply and drainage engineering, heating project, firefighting system, municipal electrical engineering, interior decoration, road, external decoration, building works, and greening project. The operation of the industrial parks included in the system boundary is based on electricity, heat, and water consumption. In the dismantling phase, material inputs of both disposal and recycling are combined. The system boundary of the evaluation is depicted in Figure 2.

The analysis took into account the entire life cycle of this industrial park. The construction of this industrial park takes 20 months while the operation period is expected to be 47 years and 4 months.

3.4. Data Sources. Data for the LCHE industrial park is kindly provided by the developer, Beijing Economic-Technological Development Area. The data include the price and quantity of construction materials in construction as well as operation phases, and environmental inputs. The raw data are then converted to economic, greenhouse gas emission, and embodied energy flows. The greenhouse gas emission and embodied energy coefficients are derived from LCB [33] and LCE [34].

4. Results and Discussions

4.1. Environmental Emissions. Based on steps of the life cycle analysis introduced in Section 3, we calculated the greenhouse gas emission of the LCHE industrial park by multiplying the raw data provided by the developer and the greenhouse gas emission intensity data derived from LCB and LCE. The total GHG emission of the construction, operation, and dismantling stages is 1.79×10^6 tCO_2-equivalent. Figures 3 and 4 demonstrate the GHG emission in the construction and operation phases of the lifetime of the LCHE industrial park. The greenhouse gas emissions from the construction phase comprise a relatively small proportion compared with the operation stage. In the construction stage, the largest three emitters are the building works (59.71%), interior decoration project (20.33%), and

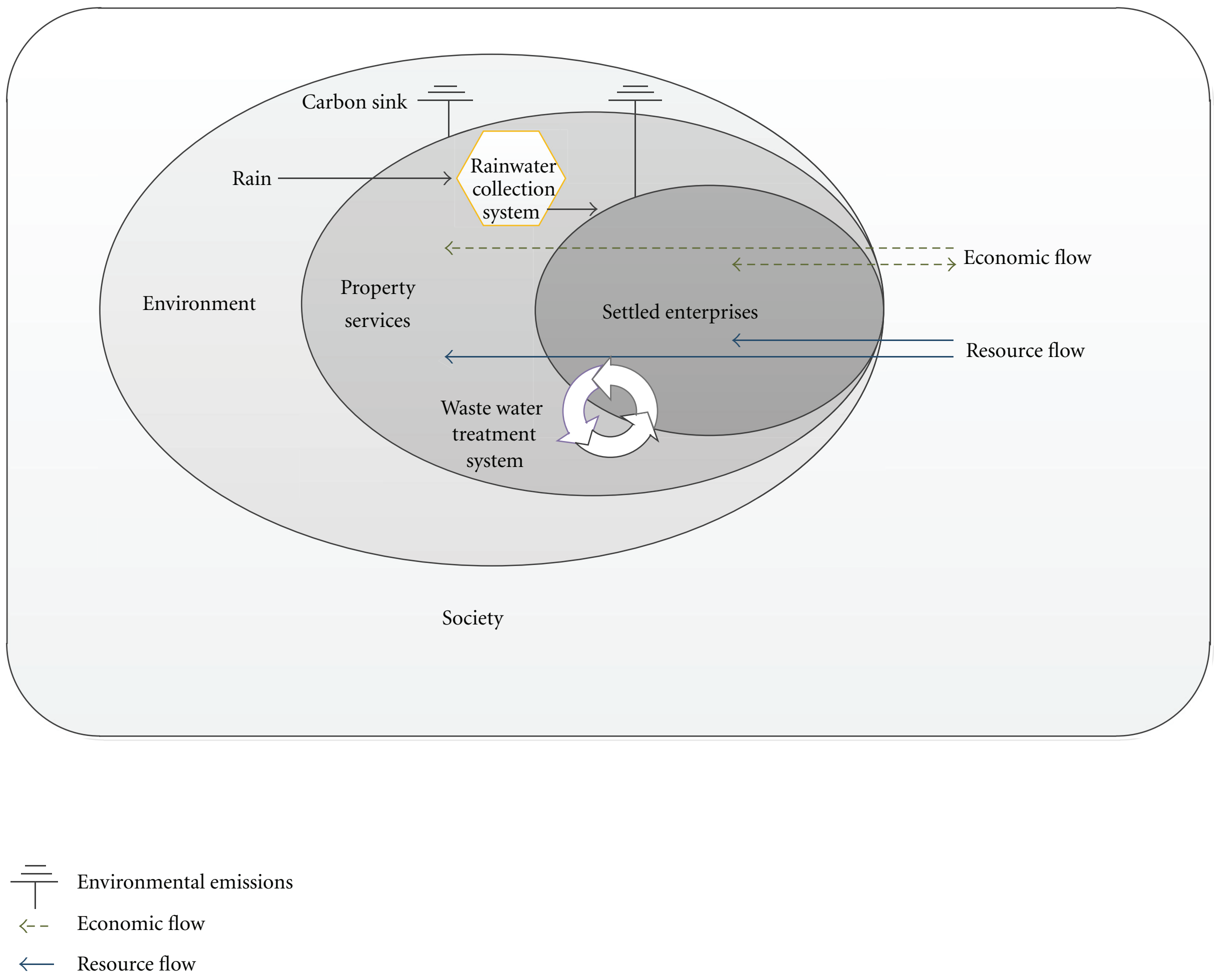

Figure 1: Components of the LCHE industrial park.

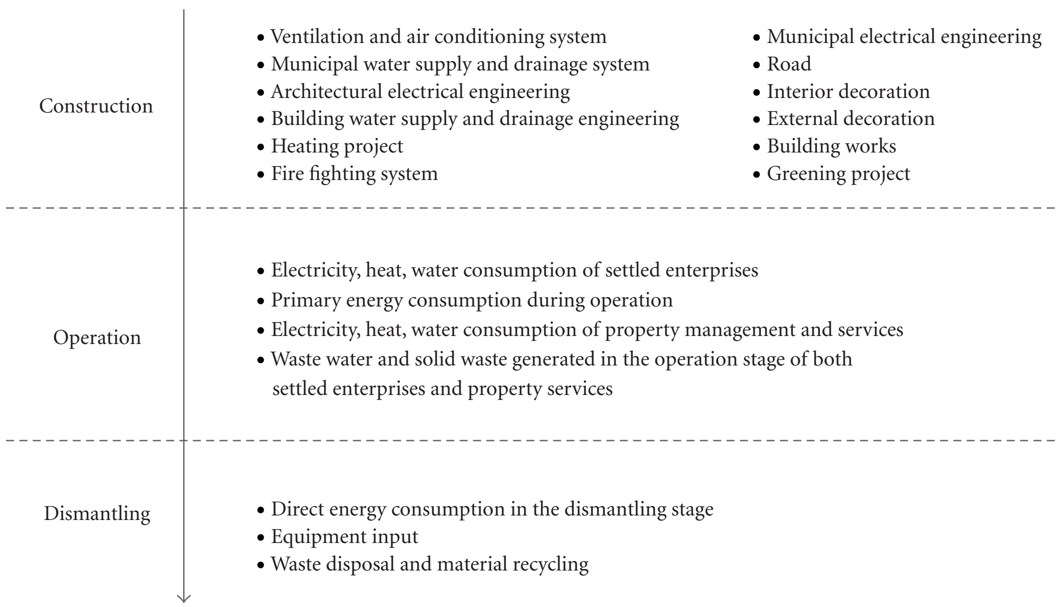

Figure 2: System boundary of sustainability evaluation.

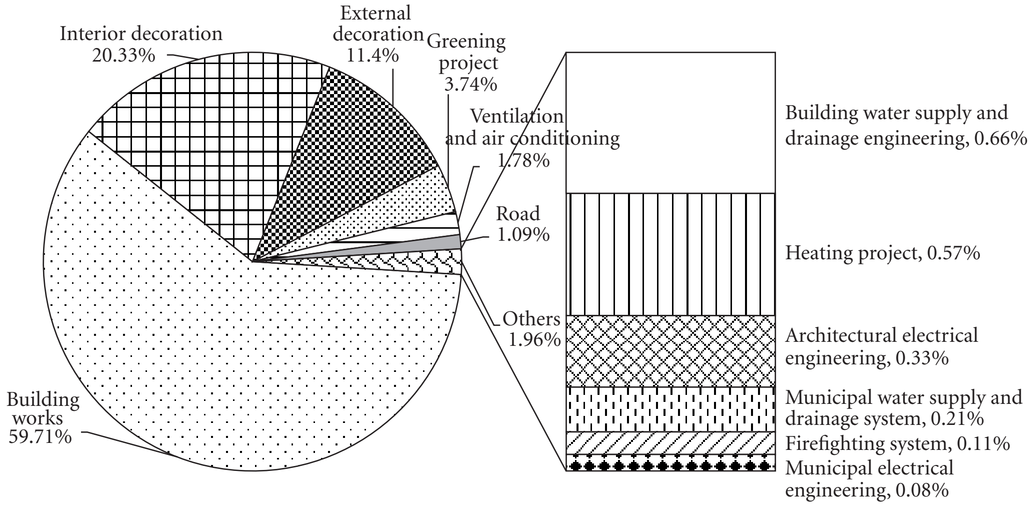

FIGURE 3: Greenhouse gas emission sources of the construction phase.

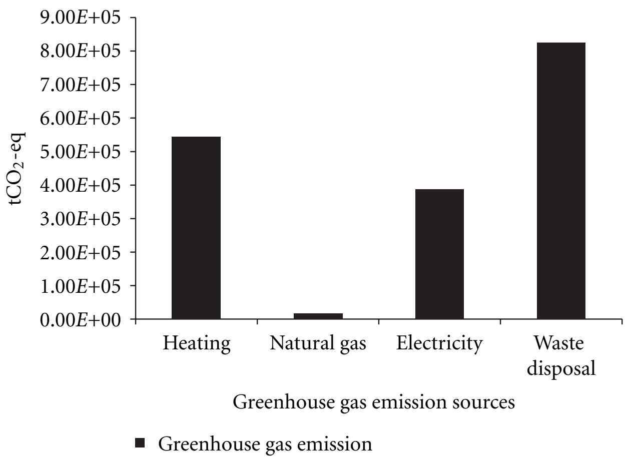

FIGURE 4: Greenhouse gas emission sources of the operation phase.

external decoration project (11.40%), followed by the greening project (3.74%), ventilation and air conditioning system (1.78%), and road (1.09%). The other 7 projects only occupy 1.96% of the total construction emission.

The operation stage is the largest contributor of this industrial park. In the operation stage, greenhouse gas emission from waste water treatment makes up the largest proportion of total emission. Greenhouse gas emission from direct energy consumption (natural gas) only occupies a small fraction of 0.11%. Although the consumption of electricity and heat do not generate on-site greenhouse gas emission, the greenhouse gas emission embodied in the electricity and heat generation process should not be ignored. When the indirect greenhouse gas emission of electricity and heat generation is traced and included, the utilization of heat and electricity make up proportions of 31% and 22% of the total operation GHG emission. Dismantling makes up the smallest proportion at 0.56%, which is mainly caused by the consumption of diesel.

The greenhouse gas emission density of the LCHE industrial park in the construction stage is 272 $kgCO_2$ eq/m^2, indicating that 272 kg greenhouse gas emission is generated per m^2 construction area. Compared with some traditional buildings such as new-build dwellings (403 $kgCO_2/m^2$) [35], and a 3 bedroom semi-detached house (405 $kgCO_2/m^2$) [36], the greenhouse gas emission density is much lower, representing that the LCHE industrial park has great carbon reduction potential.

The greening rate of the LCHE industrial park is 41%, which is much higher than the value set in the “Evaluation Standard for Green Building” of China (30%) [37]. As green space performs as a carbon sink, the coverage of green land is beneficial for greenhouse gas mitigation for the LCHE industrial park. Using the accounting framework of IPCC [38], the annual greenhouse gas emission absorbed by green land in this industrial park is calculated to be 106.73 tCO_2/year.

Greenhouse gas emission intensity in the operation stage is 2.77×10^{-3} $kgCO_2$ eq/\$, which is lower than that of the construction industry (4.87×10^{-3} $kgCO_2$ eq/\$) and the Wholesale, Retail Trade and Hotel, Restaurants industry (3.36×10^{-3} $kgCO_2$ eq/\$) [39, 40]. Obviously, when one unit of economic output is delivered, less greenhouse gas is emitted from the LCHE industrial park. Thus, it can be regarded a success practice in promoting the development of a low carbon economy.

When taking dismantling into consideration, the GHG emission should exclude the emission avoided by material recycling. As the LCHE industrial park is under operation, no detailed data on the disposal of building materials are available. A principle used by Kabir et al. [41] in material disposal and recycling has been employed for the calculation of greenhouse removal rate, based on which the greenhouse gas removal rate is calculated to be 15.73%.

4.2. Economic Investment. The total investment on the construction of the LCHE industrial park is $\$6.15 \times 10^7$,

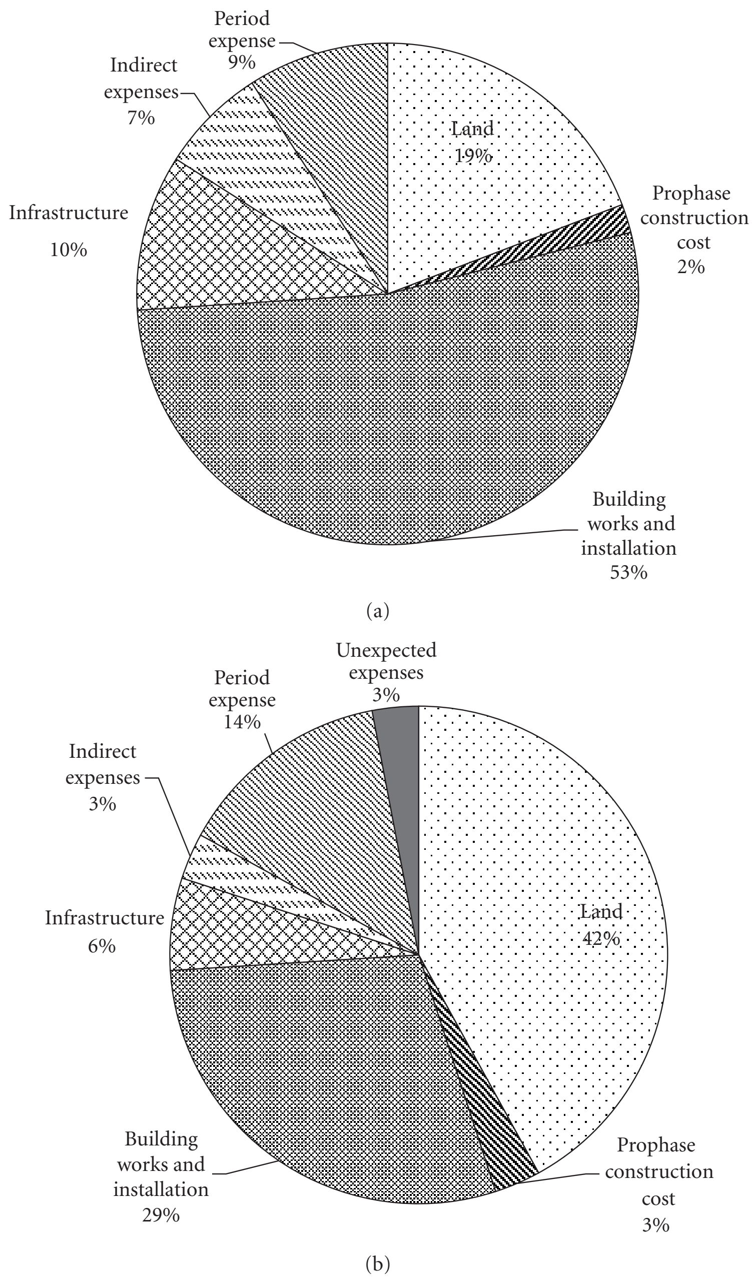

Figure 5: Investment structure of the LCHE industrial park and the average real estate investment in China ((a) LCHE industrial park, (b) the average China).

in which the costs of prophase construction, building works and installation costs, infrastructure costs, indirect expenses, period expenses, and land fees constitute 2%, 53%, 10%, 7%, 9%, and 19%, respectively, (Figure 5(a)). Obviously, investments in building works and installation make up the largest proportion. It can be thus concluded that the fluctuations of construction material price exert the largest influence on economic indicators.

Compared with the investment structure of the average real estate in China (Figure 5(b)), the proportion of investment in land in the LCHE industrial park is relatively low. The building works and installation expenses of 53%, which is much higher than that of the average China, can be attributed to the utility of low carbon building materials, which is more expensive than traditional building materials. As a complete infrastructural facility has been installed in this LCHE industrial park, the proportion of infrastructure costs is higher than that of the average China. The indirect fee of the LCHE industrial park is lower than that of the average China, implying the necessity of improving managerial efficiency of the construction and avoiding unnecessary expenses.

Figure 6 demonstrates the economic indicators of different industrial parks. The USA dollar (exchange rate

Table 2: Comparisons of heat and electricity consumption of different industrial parks [32].

Industrial parks	Heat consumption density per year (GJ/m^2)	Electricity consumption density per year (GJ/m^2)
The LCHE industrial park	1.08	0.15
Wood import and manufacturing of wooden playgrounds	0.72	0.36
Manufacturing of moulds	0.72	0.36
Retail and distribution of sports equipment	0.54	0.5
Transportation and storage	1.45	0.69
Distribution of agricultural products	1.71	4.66

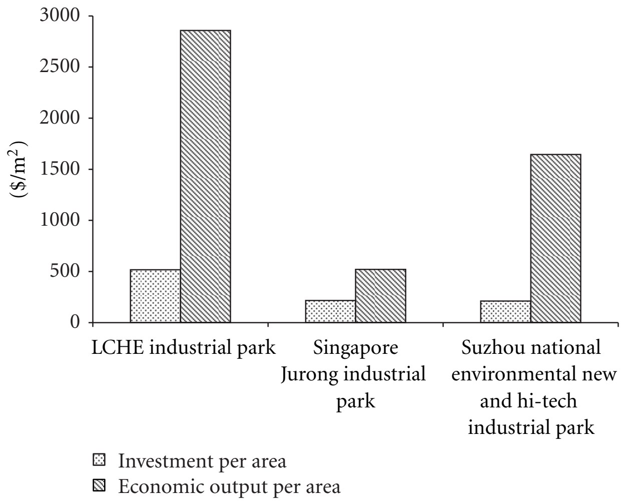

Figure 6: Economic indicators of different industrial parks.

\$1 = 6.3 yuan RMB) was used as the currency unit for global comparison purposes. Apparently, the LCHE has the highest investment per area, which implies that the construction of low carbon industrial park is not that economically competitive compared with other eco-industrial parks. However, the economic output per area of the LCHE industrial park is much higher than the other two eco-industrial parks. It accounts for the settlement of high-end and high valued added enterprises, which is regarded an "engine" for regional economy economic structure upgrading. High-end and high valued added enterprises are now emerging economic entities which should be emphasized in the entrance permission system of industrial parks.

4.3. Resource Depletion. The structure of embodied energy consumption in the construction phase is similar with the distribution of the greenhouse gas emission discussed in Section 4.1. In the operation phase, the heat consumption makes up the largest proportion, followed by the electricity consumption. Energy consumption of natural gas and the waste disposal only constitute a small fraction. In the dismantling phase, the embodied energy consumption constitutes only 0.71%, which can be neglected.

Energy density of the LCHE industrial park is calculated to be 1.31 GJ/m^2, much lower than the conventional dwelling building (3.25 GJ/m^2) [42], which implies that the LCHE industrial park is a promising approach in reducing energy depletion in the building industry. The energy intensity in the operation stage is calculated to be 0.12 GJ/m^2. The comparisons of heat and electricity consumption with other EIPs are listed in Table 2. The heat density of the concerned LCHE industrial park is higher than some manufacturing and tertiary industries, and lower than the transportation industry. Heat consumption in this industrial park should thus be controlled. The electricity consumption density of the LCHE industrial park is the lowest, meaning that the electricity consumption in the LCHE industrial park can satisfactorily meet the demand of low carbon and energy-saving lifestyle.

In the LCHE industrial park, waste water generated in the operation phase is treated by the waste water treatment system. The treated water is then recycled and reused to satisfy daily water demand in the park. In the "Evaluation Standard for Green Building" of China, the proportion of unconventional water should constitute more than 10% of the total water consumption [37]. The water recycling rate of the LCHE industrial park is 50.80%, which is much higher than the national standard of green buildings.

Owing to material recycling, energy embodied in materials like steel, copper, and so forth, can be recycled and reused. According to the discipline of Kabir et al. [41], energy reduction rate of the LCHE industrial park is 10.30%, which is lower than the specified 30% for green buildings [37]. Further plans that can improve the energy reduction rate should be made to qualify a low carbon and energy-saving industrial park in terms of dismantling and disposal.

5. Conclusions

Along with the enforcement of the blossom of low carbon economy in China, the eco-industrial parks and low carbon industrial parks have been developing in an unprecedented way. To probe into the sustainability of low carbon industrial parks and make tradeoffs with traditional parks, in this paper, embodied energy, greenhouse gas emission, and economic aspects of sustainability for a LCHE industrial park in Beijing, China, are monitored by proposing an evaluation framework with a series of indicators. In combination with the life cycle analysis, the evaluation framework assessed the whole lifetime sustainability of the industrial park.

From the embodied energy use and greenhouse gas emission perspectives, compared with other industrial parks or green buildings, it is obvious that the LCHE industrial park is a good choice for both energy savings and greenhouse gas emission reduction. In addition, in the whole lifetime of the LCHE industrial park, the greenhouse gas emitting from operation stage contributes most to the total emissions and embodied energy consumption. This indicates that the emphasis of low carbon industrial park management should be laid on building up a low-carbon lifestyle.

In addition, in the construction phase, building works is the main component that affects the environment and resource use most. Thus, the selection of low carbon material is the key point. Meanwhile, manufacturers should pay attention to the optimization of manufacturing processes in order to produce low carbon products. It is also promising to look more closely into ways of material recycling and reusing building materials, which may make great contributions to both energy saving and greenhouse gas emission reduction.

Based on the economic indicators, the overall results indicate that the investment is relatively higher than that of other industrial parks. There is thus a necessity of improving managerial efficiency of the construction and avoiding unnecessary expenses. In view of profit gained, the LCHE industrial park is much more economically profitable owing to the settlement of high end enterprises. This is a new economic cluster mode which will be an inevitably prevalent trend in China.

Moreover, this indicator system is only a preliminary work, which should be further improved, for example, to make the social aspect of sustainable development included. Also, more case studies should be conducted and compared to make tradeoffs and shed light on future development pathways of industrial parks.

Acknowledgments

This study was supported by the Key Program of National Natural Science Foundation (nos. 50939001 and 41271543) and Program for New Century Excellent Talents in University (NCET-09-0226). The authors are especially grateful for the financial support from Beijing Development Area Co. Ltd.

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The Scientific World Journal
Volume 2012, Article ID 591343, 8 pages
doi:10.1100/2012/591343

The ScientificWorldJOURNAL

Research Article

Assessment for Fuel Consumption and Exhaust Emissions of China's Vehicles: Future Trends and Policy Implications

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Received 7 September 2012; Accepted 1 November 2012

Academic Editors: B. Chen and Z.-M. Chen

In the recent years, China's auto industry develops rapidly, thus bringing a series of burdens to society and environment. This paper uses Logistic model to simulate the future trend of China's vehicle population and finds that China's auto industry would come into high speed development time during 2020–2050. Moreover, this paper predicts vehicles' fuel consumption and exhaust emissions (CO, HC, NO_x, and PM) and quantificationally evaluates related industry policies. It can be concluded that (1) by 2020, China should develop at least 47 million medium/heavy hybrid cars to prevent the growth of vehicle fuel consumption; (2) China should take the more stringent vehicle emission standard V over 2017–2021 to hold back the growth of exhaust emissions; (3) developing new energy vehicles is the most effective measure to ease the pressure brought by auto industry.

1. Introduction

During the past decade, China's automotive industry has experienced a dramatically growth. Since 2009 China had become the largest vehicle producer and consumer. Auto industry has become a pillar industry in China's national economy and played an increasingly important role in economic development, employment promotion and domestic demand stimulation.

In recent years, the auto industry in developed countries has tended saturated state, with a slow growth (e.g., America) even a negative growth (e.g., Japan and Germany) in vehicle population. However, compared with developed countries, the per capita car ownership in China is very low and auto industry is still in a rapid increasing period. By the end of 2008, China's vehicle population was 51 million, just ranked 3rd after America and Japan (Table 1), and by August 2011, it has reached 93.5 million, second only to America (about 240 million) in the world. On a global scale, per capita car ownership is 0.15, while China's is 0.06, only 40% of the world average level. Calculated by the average level of the world, vehicle population in China should be 207 million, and that should reach 1.24 billion according to the American average level of 0.82 cars per capita. Obviously, it would bring severe challenges for China, including resource demand and exhaust emissions.

In fact, the crude oil consumption in China had reached 383.845 million tons in 2009, with average annual growth rate of 6.5% from 1990s, which is 4 times greater than the world growth rate (1.5%) over the same period. One of the major drivers of this increase in China's oil consumption is the rapid growth of the transportation sector in general and motor vehicles in particular [1]. About 60% of China's oil consumption in 2009 was for transportation [2]. Similarly, vehicle exhaust emissions grew from 17.24 million tons in 1995 to 40.555 million tons in 2009, with an annual average growth rate of 6.3% [3]. Thus, while auto industry expands rapidly, these environmental problems will become more stand out, seriously impeding the sustainable development of China.

Concerning the rapid development of the auto industry in China, scholars in the recent years have begun to keen to study a series of environmental issues associated with auto industry, analyzing the status, and predicting the future development. For example, Yan and Crookes [4] set two scenarios, best case scenario and baseline scenario, to assess the reduction potentials of energy demand and greenhouse gas (GHG) emissions in China's road transport sector till

Table 1: Worldwide vehicle population and per capita car ownership in 2008.

Country	Vehicle population/10^4	Per capita cars
USA	25024	0.82
Japan	7553	0.59
China	5100	0.04
Germany	4400	0.54
Italy	4089	0.69
Russia	3826	0.27
France	3721	0.60
Britain	3562	0.58
Spain	2761	0.60
Brazil	2748	0.14
Mexico	2531	0.24
Canada	2052	0.62
Poland	1909	0.50
India	1851	0.02
Korea	1679	0.35
Australia	1468	0.67
Turkey	1019	0.15
Thailand	977	0.15
The Netherlands	891	0.52
Argentina	846	0.21
Indonesia	825	0.04
South Africa	749	0.15
Belgium	586	0.53
Sweden	480	0.53
Austria	468	0.59
Switzerland	436	0.62
Others	15752	0.07
Total	97306	0.15

Data resource: National Bureau of Statistics of China, Japan Automobile Manufacturers Association, German Automobile Industry Association, Ward's Auto, and ANFIA.

2030. Hao et al. [5] established a bottom-up model to deliver the future trends of fuel consumption and life cycle GHG emissions by China's on-road trucks.

Meanwhile, the study in this field is also hot around the world. Dargay and Gately [6] analyzed and predicted the worldwide vehicle shock from 1960 to 2015, on the view of per capita income. Bastani et al. [7] predicted the uncertainty on US transport-related GHG emissions and fuel consumption out to 2050 and got the view that developing new energy vehicles is the necessary choice for auto industry, but negative influences brought about should not be ignored. Kloess and Müller [8] assess the energy consumption and GHG emissions on the passenger car fleet in Austria, from the aspect of policy, energy prices, and technological progress, and then concluded that material cuts and appropriate taxation on fuels and cars are positive measures for the development of auto industry. In addition, scholars also did studies on different fields, such as fuel types, energy efficiency, and industry policy, and discussed the fuel consumption and GHG emission in Malaysia [9], Europe [10, 11], China [12], and other countries [13].

However, the current literature focus little on quantification of specific implementation effects of auto industry policies. Additionally, the concentration on vehicle emissions is much more on GHG [4, 7–13] while it is little on the prediction of air pollutants (such as CO, HC, NO_x, and PM). This paper aims to make up the defects in research, by predicting and evaluating the growth of auto industry in China during the next few decades, including vehicle population, fuel consumption, and vehicle exhaust emissions.

2. Prediction of Vehicle Population

2.1. Methodology. The change of vehicle population should be traced back to the combined actions of inner needs and external environmental restrictions, which could be properly described by Logistic equation. Logistic equation is a model to describe the trend of dependent variable over time. It can properly reflect the market expansion of new products [14] and shows the following characters: slow growth of the dependent variable at the initial stage, then experiencing a rapid increase stage, finally entering a market saturation stage.

As stated above, the total number of vehicles in China has been considerable. However, from the perspective of per capita car ownership, the auto industry in China is just at the primary phase, comparing with developed countries and even the world average level (Table 1). Thus, this paper assimilated China's auto industry to a market expansion process of new product and then forecasted the developing trend of China's vehicle population according to Logistic model.

Compared with other similar prediction models, for example, the Gompertz model [19, 20], the superiorities of Logistic model can be concluded to two aspects: few constraint conditions, and only one parameter estimation which the whole process involves. In fact, there have been some works in the literature applying Logistic model to the prediction of vehicle population in other countries. Button et al. [21] modeled vehicle ownership and use in five groups of low-income countries by quasilogistic model. Singh developed projections for future mobility in India, based on Logistic and Gompertz models, respectively [22].

The differential form of Logistic model can be expressed as [23]

$$\frac{dF_t}{dt} = aF_t(1 - F_t), \tag{1}$$

where $F_t = N_t/N_m$, N_t represents vehicle population at moment t, N_m is the maximum based on the market, and a is the instantaneous rate of increase, a constant. While $(1-F_t) > 0$, the vehicle population increases; while $(1-F_t) < 0$, it decreases; while $(1 - F_t) = 0$, it remains stable.

Table 2: Vehicle population from 1978 to 2008 in China.

Year	1978	1979	1980	1981	1982	1983	1984	1985
Population	142.92	156.57	168.10	187.30	205.32	222.71	243.37	288.71
Year	1986	1987	1988	1989	1990	1991	1992	1993
Population	357.45	412.29	477.64	527.47	583.59	611.41	701.47	817.58
Year	1994	1995	1996	1997	1998	1999	2000	2001
Population	941.95	1040.00	1100.08	1219.09	1319.30	1452.94	1608.91	1802.04
Year	2002	2003	2004	2005	2006	2007	2008	
Population	2053.17	2382.93	2693.71	3159.66	3697.35	4358.36	5099.61	

Unit: 10^4.

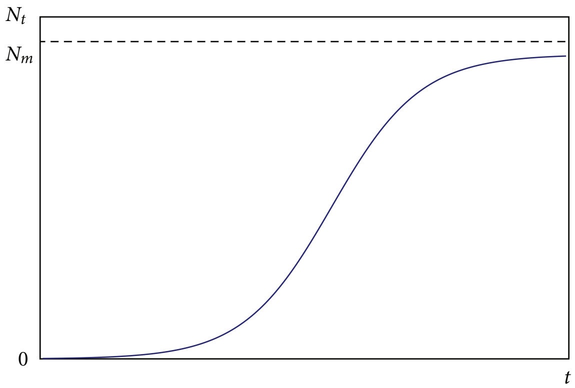

Figure 1: Logistic model curve.

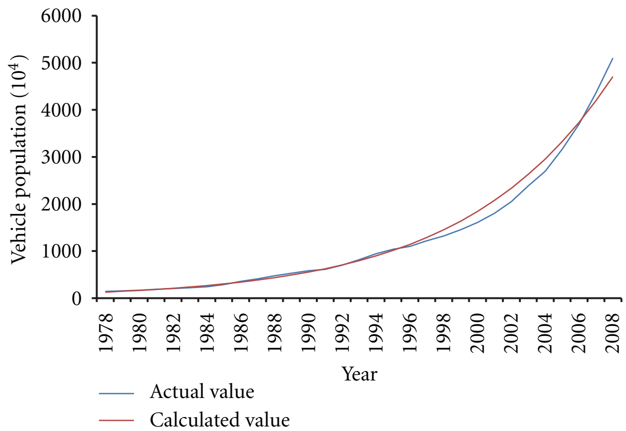

Figure 2: Comparison of calculated vehicle population and actual value.

Solving (1) by separating variables, we can see that

$$F_t = \frac{1}{1 + e^{-(b+at)}}, \tag{2}$$

where b is a constant. Equation (2) is shown in Figure 1, which indicates that the Logistic model is an S-shaped growth curve. A feedback regulation exists among three variables (F_t, $(1 - F_t)$, a), which makes vehicle population tend to the maximum N_m.

Take the logarithm of (2):

$$\ln \frac{F_t}{1 - F_t} = at + b. \tag{3}$$

It can be concluded from (3) that $\ln F_t/(1 - F_t)$, with t, constitutes a linear relationship. Hence, estimating a maximum population value N_m based on the actual situation of our country, then figuring out $\ln F_t/(1 - F_t)$, we can get the model parameters (a and b).

2.2. Model Calculation and Estimation Results. This paper consulted the per capita car ownership data (Figure 1) and population densities of developed countries to estimate N_m. In 2008, Americans owned 0.82 cars per capita, while this value ranged from 0.54 to 0.69 in some other developed countries, such as Japan, Germany, Italy, Britain, France, and Spain. The auto industries had developed to a mature period in these countries above, even showing a negative growth since 2007 in the US, Japan, and Germany. Moreover, while the population density in the US (32 people per km^2) was low, the value in Italy (196 people per km^2) and France (113 people per km^2) was closer to that in China (138 people per km^2). Thus, this paper assumed that the per capita car ownership in China would be 0.6 when reaching the maximum. Suppose that Chinese population would keep around 1.4 billion in the next few decades, so N_m was calculated to be 840 million.

Calculate the model parameters (a and b) by (3) and show the result in (4). The original data were the statistic vehicle population in China from 1978 to 2008 (Table 2):

$$\ln \frac{F_t}{1 - F_t} = 0.1217t - 6.5971. \tag{4}$$

The correlation coefficient R^2 of (4) was 0.9932, showing a good linear relationship. Draw the calculated curve by (4) and compare with the actual value in Figure 2. The fitting degree in Figure 2 was tested to be 98.76%, which could guarantee the validity of this model.

The forecast outcome of future vehicle population in China was shown in Figure 3. The vehicle population in China would reach 171.02 million in 2020 and then enter a high speed growth period. In 2035, it would achieve 515.23 million, and at the same time the growth rate would begin to slow down. Around 2050, the vehicle population would have been 762.55 million, and then it would turn into a smooth growth period. Thus, the vehicle population in China should

Table 3: Statuses and planning targets of domestic and foreign vehicle average fuel consumption per hundred kilometers per car.

	Current	2015	2020	2025
China	8.25[1]	7.5[2]	5.78[3]	—
Japan	6.13 [15]	—	4.93 [15]	—
EU	6.13 [16]	5.46 [15]	3.99 [15]	2.94 [16]
USA	7.50 [15]	—	—	4.31 [15]

Unit: L/100 km.
Tips: [1]8.25 = (1 + 0.1) × 7.50, according to the report that current fuel consumption in China was 10% higher than that of USA (available on http://www.find800.cn/news/bus/ye/110930/12778.html).
[2]7.5 = 7 × 0.75 + 9 × 0.25, according to [17, 18] and weights for passenger car and commercial car in China.
[3]5.78 = 5 × 0.75 + 8.1 × 0.25, the same as Tip 2.

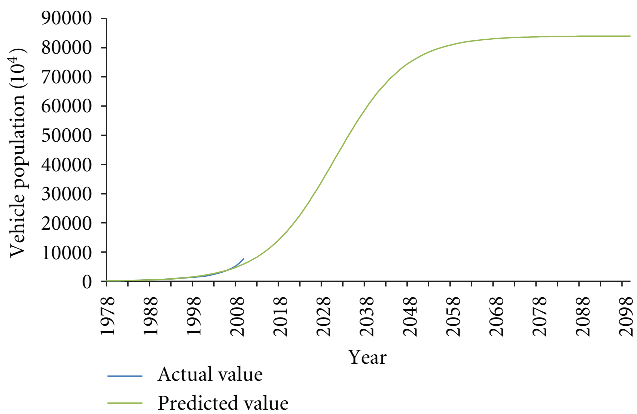

Figure 3: Prediction curve of future vehicle population in China.

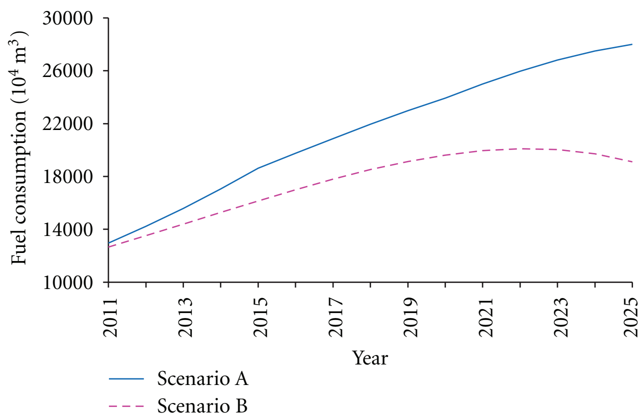

Figure 4: Forecast curve of China's vehicle fuel consumption from 2011 to 2025.

run through a quite rapid growth period inevitably over 2020–2050. Moreover, the enormous environmental pressure followed would bring China huge challenges, such as fuel consumption, exhaust emissions, and scrap car disposal.

3. Prediction of Fuel Consumption

According to the average vehicle fuel consumption per hundred kilometers and future vehicle population predicted above, this paper proposed a prediction of fuel consumption of future auto industry in China. The equation was as follows:

$$V_t = 10^{-5} \cdot v_t S N_t, \tag{5}$$

where V_t is the total vehicle fuel consumption of China in year t, 10^4 m^3; v_t is the average fuel consumption per hundred kilometers per car in year t, L/100 km; S is the annual average driving distance per car in China, km; N_t is the predictive value of vehicle population in year t, 10^4.

In addition, v_t could be calculated on the basis of current statuses and planning objectives both in China and overseas (Table 3). The value of S was 2.42×10^4 km, according to Table 3 and the total fuel consumption in 2010.

3.1. Scenario Prediction. Depending on different planning objectives for fuel consumption per hundred kilometers, it is proposed to set the following two scenarios.

Scenario A. In terms of average fuel consumption per hundred kilometers, Chinese auto industry develops under the current domestic set of development goals, which is described as the 1st line in Table 3.

Scenario B. The average fuel consumption of hundred kilometers in China will reach the world's most advanced level in 2025, which is equivalent to the EU fuel consumption level (the 3rd line in Table 3). That is to say, in 2018 the average level in China is assumed to achieve 5.46 L/100 km, the level of EU in 2015, and in 2025 it should achieve 2.94 L/100 km, equal to that of EU.

Calculate all the data in (5) and attain the forecast value of fuel consumption under the above two scenarios, shown in Figure 4.

In Scenario A, the fuel consumption in China will increase year by year in the next 15 years, with no trend to slow down. In 2022, the fuel consumption (239.07 million m^3) will be twice than that in 2011 (121.31 million m^3). In Scenario B, the fuel consumption will achieve the largest in 2022 (185.10 million m^3) and then begin to decline. The accumulative fuel consumptions from 2011 to 2025 will have been 2.3 billion tons and 1.9 billion tons, respectively. However, the Chinese oil reserve was only 2.95 billion tons in 2009. According to the developing trend in Scenario A, the oil

TABLE 4: Implementation schedule of various Motor Vehicles Emission Standard in China.

Year	2000–2003	2004–2006	2007–2010	2011	2012	2013
Emission standard	I	II	III		IV in batches	

TABLE 5: Annual emissions of 4 pollutants for various standards.

	I before	I	II	III	IV[1]
CO	1.4648	0.6421	0.2107	0.0715	0.0286
HC	0.1809	0.0662	0.0221	0.0110	0.0044
NO_x	0.2477	0.0977	0.0400	0.0200	0.0080
PM	0.0296	0.0099	0.0036	0.0010	0.0004
Total	1.9230	0.8159	0.2766	0.1035	0.0414

Unit: tons/car.
Data resource: *China Vehicle Emission Control Annual Report (2010)* [3].
Tip: [1]According to news report, the data for Standard IV was 60% lower than Standard III (Available on http://auto.qq.com/a/20050530/000043.htm).

reserve in China would be depleted out before 2030 without relying on oil import.

3.2. Fuel Consumption Policy Evaluation. In July 2012, China has officially released Energy Saving and New Energy Vehicles Industry Development Planning (2012–2020) (hereinafter referred to as the "*Planning*"), which detailed goals of energy saving and new energy vehicles in China. In *Planning*, there are two stage goals on the market share of new energy vehicles: (1) up to 2015, the number of pure electric vehicles (PEVs) and plug-in hybrid electric vehicles (PHEVs) should outnumber 0.5 million, and medium/heavy hybrid cars should reach one million; (2) up till 2020, the number of PEVs and PHEVs should reach 5 million, and medium/heavy hybrid cars should popularize on a large scale.

To assess the effect of *Planning*, this paper contrasts it with the two scenarios above, shown in Figure 5. From Figure 5, we can see that according to *Planning*, the fuel consumption in China would still keep in a rising trend, but since 2015 the growth will slow down significantly. The fuel consumption would be 1.18% lower than that in Scenario A by 2015, and 9.72% lower by 2020. Thus, we conclude that developing new energy vehicles is the absolutely necessary to reduce the fuel consumption in China. However, to achieve the world's most advanced level, the developing track in Scenario B, China would continue to reduce to 86% of the total fuel consumption by 2015, and 89% by 2020, on the base of *Planning*. That is, by 2020, under the premise of completing the target of 5 million PEVs and PHEVs, medium/heavy hybrid cars should be developed to 47 million at least, which is equivalent to 60% of current domestic vehicle population. Thus, China faces difficult challenges to reduce the vehicle fuel consumption.

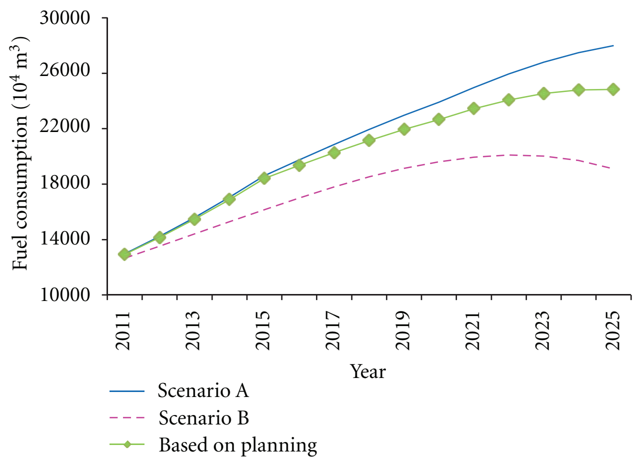

FIGURE 5: Forecast curve of China's vehicle fuel consumption under the implementation of *Planning*.

4. Prediction of Exhaust Emissions

Since 2000, when Motor Vehicles Emission Standard I implemented, China has implemented 4 emission standards, as shown in Table 4. According to *China Vehicle Emission Control Annual Report (2010)* [3], the reduction effects of stringent implement of motor vehicle emission standards emission is very significant. In 2009, vehicles produced before Standard I, which just accounted for 17.1% of the total, discharged four main pollutants (CO, HC, NO_x, and PM) in excess of 50%, while vehicles produced after Standard III, which made up 25.4% of the total, only discharged 4% of the four pollutants.

4.1. Scenario Prediction. To predict and assess changes of four major pollutants (CO, HC, NO_x, and PM) in vehicle emissions, the paper intends to figure out the annual vehicle exhaust emissions by:

$$M_{t,k} = \sum_i m_{t,k} N_{i,t}, \tag{6}$$

where $M_{t,k}$ is the emissions of pollutant k in year t, $10^4 t$; $m_{i,k}$ is the annual emissions of pollutant k per car performing Standard i (Table 5), t; $N_{i,t}$ is the predictive value of vehicle population performing Standard i in year t, 10^4; i presents Standard I before, Standard I, Standard II, Standard III, and

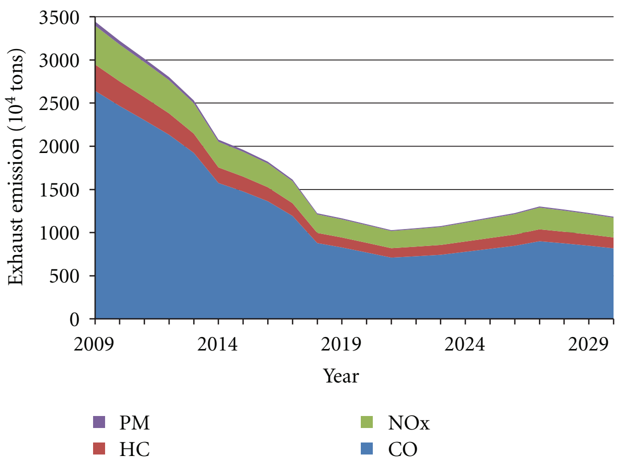

FIGURE 6: Forecast curve of China's exhaust emissions in Scenario A.

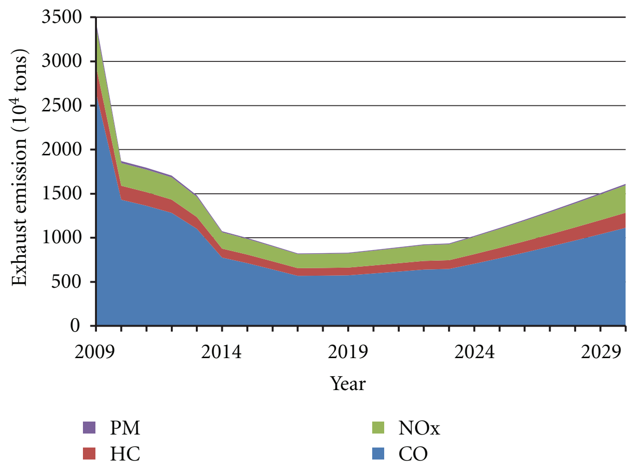

FIGURE 7: Forecast curve of China's exhaust emissions in Scenario B.

Standard IV; k presents the four main exhaust pollutants, that is, CO, HC, NO_x, and PM.

$N_{i,k}$ is calculated by the relation of vehicles scrapped and vehicle sales per year. Accounting for the different vehicle life cycles, it is proposed to set the following two scenarios.

Scenario A. The vehicle life cycle is 15 years, the maximum prescribed years in *Motor Vehicle Rejection Standard (1997)* [24]. That is, vehicles before Standard I would be fully scrapped till 2014, by the same token, vehicles performing Standards I, II, and III would be fully scrapped, respectively till 2018, 2021, and 2027, while new vehicles would perform Standard IV.

Scenario B. The vehicle life cycle is 11 years, which is calculated according to *Motor Vehicle Rejection Standard (1997)* [24] and the portion of different vehicle types. Thus, vehicles before Standard I would be fully scrapped till 2010, by the same token, vehicles performing Standards I, II, and III would be fully scrapped, respectively till 2014, 2017, and 2023, while new vehicles before 2013 would perform Standard III, then would perform Standard IV.

The prediction curves of China's four major pollutants in vehicle emissions under two scenarios are shown in Figures 6 and 7. It can be found that changes of four pollutants are roughly consistent under the two settings and show a trend that first decreases and then grows. At the lowest point, total emissions, respectively, amount to 10.28 million tons in 2021, and 8.22 million tons in 2017.

It can be concluded that prior to these two time points (2021 in Scenario A, and 2017 in Scenario B), the current implementation of emission standards would continue to play a role in the next 5–10 years, and then the increase in vehicle population would surpass the constraint function of Standard IV, resulting in the regrowth of pollutant emissions. Thus, to ensure the exhaust emissions growth, China should take the more stringent emission standard V at least in 2017–2021.

4.2. Exhaust Emission Policy Evaluation. Further analysing the two scenarios and evaluating the effectiveness of emission standard V, we make two assumptions: firstly, Standard V was 60% lower on the basis of Standard IV, referring the reduction effects of Standard I to Standard IV; secondly, Standard V would be implemented after the time points of lowest emissions (2021 in Scenario A, and 2017 in Scenario B). The prediction curves are shown in Figures 8 and 9. It can be seen that, due to the timely implementation of Standard V, China's vehicle pollutant emissions continue to decline, but the rate is slowing down. Under Scenario B, emissions of the four pollutants restart the upward trend after 2028. However, Table 5 shows that the annual emission of four pollutants per car performing Standard V is only 0.016t, about 1/100 of that of vehicles before Standard I. If only implementing emission standard VI, rather than taking other measures, it would achieve little success, comparing the rapid growth of vehicle population. Therefore, to further control vehicle exhaust emissions, China should actively develop new energy vehicles, on the basis of continuing to strengthen phased emission standards.

5. Conclusions

In this paper, we developed a prediction of vehicle population in China in the next few decades, based on Logistic model, by using a statistical data set over the period of 1978–2008. Given the per capita car ownership and population density of developed countries, we assumed that per capita would own 0.6 cars when entering the saturation state. We predicted that the total number of China's vehicles would be approximately 15 times higher in 2050 than in 2008, increasing to more than 750 million vehicles (Figure 3). It also can be concluded that China's auto industry would run through a high speed development period during 2020–2050, which would inevitably aggravate China's environmental burden.

Moreover, fuel consumption prediction over 2011 to 2025, based on the average vehicle fuel consumption per

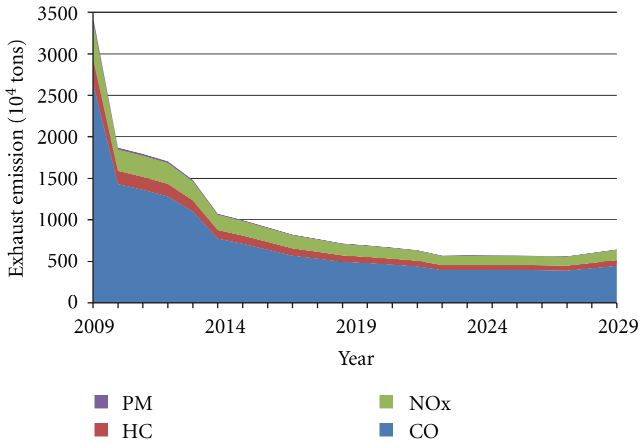

FIGURE 8: Forecast curve of China's exhaust emissions under the implementation of Standard V in Scenario A.

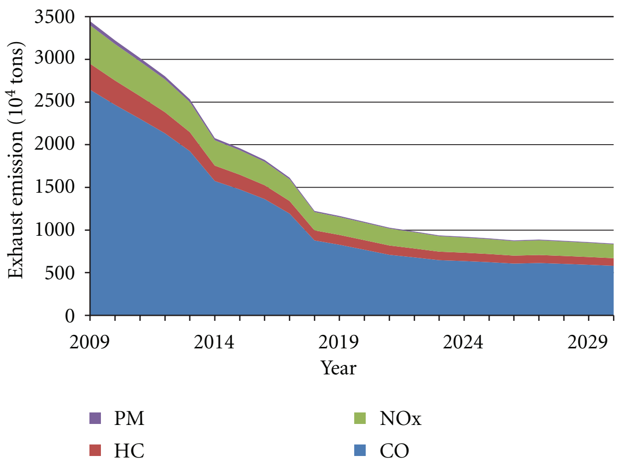

FIGURE 9: Forecast curve of China's exhaust emissions under the implementation of Standard V in Scenario B.

hundred kilometers, shows that under the current scenario, China's fuel consumption for vehicles would grow without trend to slow down, reaching 239.07 million m^3 in 2022 (Figure 4), which is the twice in 2011. However, under the world's most advanced scenario, it would peak in 2022 and then begin to decline. Considering the tension of fuel supply, the current development goals for China auto industry could not be suited to demand. Further, we evaluated *Planning*, China's latest policy for vehicle fuel consumption, and found that the growth trend of fuel consumption in China would meet a marked slowness since 2015 (Figure 5), on the basis of current development goals. Nevertheless, to achieve the world's most advanced level, China should develop medium/heavy hybrid cars to 47 million at least by 2020, under the existing premise of completing the target of 5 million PEVs and PHEVs.

Furthermore, allowing for different vehicle life cycles (the maximum and the average), exhaust emissions prediction for China's vehicles up to 2029 was developed in this paper, on the basis of vehicle emission standards for different phrases. We projected that the four pollutants (CO, HC, NO_x, and PM) would display roughly consistent changing trends under the two settings and reach the lowest points, respectively, in 2021 and in 2017 (Figures 6 and 7). Thus, in order to hold back the exhaust emission growth, China should continue to implement the more stringent emission standard V at least in 2017–2021. However, further study on the effect of emission standards showed that the Standard VI would achieve little, when it meets the rapid growth of vehicle population (Figures 8 and 9).

Finally, our results suggest that the future strong growth in China's vehicle population will bring huge burdens on fuel demand and exhaust emissions. China should actively develop new energy vehicles, which is the most effective measure to ease the pressure on fuel demand and exhaust emissions brought by auto industry.

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The Scientific World Journal
Volume 2012, Article ID 613721, 6 pages
doi:10.1100/2012/613721

The ScientificWorldJOURNAL

Research Article

Greenhouse Gas Emission Accounting and Management of Low-Carbon Community

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Received 7 September 2012; Accepted 4 November 2012

Academic Editors: N. H. Afgan, Md. Hasanuzzaman, and F. Pilo

As the major source of greenhouse gas (GHG) emission, cities have been under tremendous pressure of energy conservation and emission reduction for decades. Community is the main unit of urban housing, public facilities, transportation, and other properties of city's land use. The construction of low-carbon community is an important pathway to realize carbon emission mitigation in the context of rapid urbanization. Therefore, an efficient carbon accounting framework should be proposed for CO_2 emissions mitigation at a subcity level. Based on life-cycle analysis (LCA), a three-tier accounting framework for the carbon emissions of the community is put forward, including emissions from direct fossil fuel combustion, purchased energy (electricity, heat, and water), and supply chain emissions embodied in the consumption of goods. By compiling a detailed CO_2 emission inventory, the magnitude of carbon emissions and the mitigation potential in a typical high-quality community in Beijing are quantified within the accounting framework proposed. Results show that emissions from supply chain emissions embodied in the consumption of goods cannot be ignored. Specific suggestions are also provided for the urban decision makers to achieve the optimal resource allocation and further promotion of low-carbon communities.

1. Introduction

Global warming has been a hot topic since a few decades ago and became a direct trigger for behavior change for people worldwide [1–35]. As the most impacted region by human activities, cities emit more than 75% of the total greenhouse gas, in which CO_2 occupies a large proportion [36]. Cities play an important role in global carbon cycle, and most of their impacts are exerted via indirect pathways [37]. With the purpose of the energy resource consumption minimization and greenhouse gas emission reduction, low-carbon cities have attracted increasing attention [38]. As the cell of a city, community is the basic unit in the low-carbon city construction, and its structure and density also play a key role in energy consumption and CO_2 emission [39, 40]. Low-carbon community provides a platform for individual behavior change [41, 42]. The UK Low-Carbon Transition Plan [43] also makes explicit the major role that households and communities play in building a low-carbon future. A common viewpoint has been reached that low-carbon community will be an efficient way to achieve sustainable development due to its energy utilization, internal structure optimization, and external effects reduction. Obviously, the pursuit of low-carbon community would be extremely essential to retard the global climate change.

In order to estimate the contribution of cities to global climate change, many attempts have been made to quantify the carbon emissions associated with the accounting level in the community. Recently, many organizations have been conducting "low-carbon" projects to estimate the contributions to global climate change. Many protocols were put out to guide organizations to measure GHG emissions [44–46]. These protocols are mainly concentrated on direct emissions and indirect emissions from purchased energy, with less focus on supply chain emissions that occupied a large proportion in a community. For example, direct CO_2 emissions are found to be generated by direct household energy use, whereas indirect CO_2 emissions are generated in the industrial sectors producing nonenergy commodities demanded by the households [47]. Pachauri and Spreng applied the IO models into the calculation of direct and indirect energy consumption of households in India based on the 115-sector classification input-output tables [48]. Lu et al. quantified the direct and indirect household emissions of CO_2 in China with the help of input-output life-cycle assessment (IO-LCA) combined with 8 categories of household expenditure [49]. A calculation framework for whole life-circle carbon budget in residential area was presented based on building system, social system, and green space system, showing that the ratio of carbon source to carbon sink is 29 : 1 and that of society source to building source is 4.6 : 1 [50]. It can be seen that there is serious imbalance between carbon sink and carbon source in this residential area, and the society source is a key factor for carbon budget balance.

Moreover, Matthews et al. classified the variety scopes of carbon footprint into 3 tiers, including direct emissions, emissions from purchased energy, and supply chain emissions [51]. In their study, two case studies of book publishers and power generation were conducted, which illustrated that the first 2-tier emissions accounted for only a small part while a large portion is constituted by emissions embodied in the supply chain. The Scope 3 footprints of US economic sectors using a modified form of the 2002 US benchmark Economic Input-Output Life Cycle Assessment (EIO-LCA) model was developed to categorize upstream emission sources [52]. Larsen and Hertwich developed a greenhouse gas emissions inventory related to the provision of municipal services in the city of Trondheim, Norway, indicating that approximately 93% of the total carbon footprint of municipal services is indirect emissions [53]. The authors also established CO_2 inventories focused on the supply chain emissions of CO_2 emissions from each sector, for example, agriculture, industry, transportation, and tertiary industry, and identified the sectors that contribute the most to climate change [54].

As can be seen, the previous studies on 3-tier accounting are mainly concentrated on industry sectors, with less focus on community-level CO_2 emissions. A special focus should be transferred to identify Scope 3 categories that are relevant and incorporated into the footprint analysis. Thus, further characterization of the total supply chain emissions in community is necessary in order to achieve a better strategy for carbon emission mitigation. Approaches based on life cycle assessment (LCA) methods are available to estimate the embodied CO_2 in the consumption of goods, which provides a framework for analysis of the potential environmental impacts embodied throughout the lifetime of goods [55, 56]. There are two common types of LCA models, that is, process-based LCA and EIO-LCA, varying according to differences in system scope and analysis with its own processes and characteristics [57]. Economic IO models were first developed by Leontief in 1936 to aid manufacturing planning [58]. Compared to the process-based LCA, EIO-LCA addresses some of the drawbacks of process-based LCA model and greatly expands the system scope to include the entire economy of a region, which can assess the energy consumption and environmental impacts of goods from a nationwide perspective based on economic input-output matrix.

The aim of this paper is to propose an efficient three-tier carbon emission accounting framework for community. Taking a typical high-quality community in Beijing as case study, this study also intends to quantify the magnitude of carbon emissions and the mitigation potential using the method of LCA in combination with a detailed CO_2 emission inventory, including emissions from direct fossil fuel combustion, emissions from purchased energy (mainly contains electricity, water, and heat), and supply chain emissions embodied in the consumption of goods. Some suggestions about the realization of optimized resource allocation and further promotion of such communities are also given for the decision makers.

2. Methodology

We develop estimation equations for three tiers of carbon footprint of the community based on the scope initially developed by Matthews et al. [51].

Tier 1 includes direct emissions from household fossil fuel combustion and vehicles, including emissions from natural gas, gasoline, diesel oil, and jet kerosene. This is similar to the "consumer perspective" used for emissions inventories [59].

Tier 2 is based on Tier 1, in addition to indirect emissions from purchased energy (mainly contains electricity, water, and heat) for a community.

Tier 3 includes the total supply chain emissions embodied in the consumption of goods and activities. The accounting model and boundaries used for estimating all purchases and activities aspects in a supply chain by any sector of a community are based on EIO-LCA, which are consistent with the data structure described in Section 3.2.

The decomposition analysis is carried out in two steps. Firstly, Tier 1 and Tier 2 CO_2 emissions from household energy use are analyzed using a simple energy emission model. Secondly, Tier 3 CO_2 emissions are analyzed using an extended LCA model that also incorporates energy and emission matrices.

In terms of spatial system boundary, the total CO_2 emissions are derived from emissions from household and public area. Thus the total CO_2 emissions calculated in 3 tiers can be defined as

$$\begin{gathered} E = E_h + E_p, \\ E_h = E_{h1} + E_{h2} + E_{h3} + E_{h4} + E_{h5} + E_{h6} + E_{h7} + E_{h8} + E_{h9}, \\ E_p = E_{p1} + E_{p2}, \end{gathered} \tag{1}$$

where E is the total CO_2 emissions from community; E_h refers to all the three-tiers CO_2 emissions from household that consists of CO_2 emissions from direct energy consumption (E_{h1}), indirect energy and water consumption (E_{h2}), transport and community (E_{h3}), food (E_{h4}), clothing and footwear (E_{h5}), household appliances and services (E_{h6}), healthcare (E_{h7}), education and recreation (E_{h8}), and from buildings (E_{h9}); E_p refers to CO_2 emissions from the public area of a community that consisted of CO_2 emissions from electricity consumption (E_{p1}) and from water consumption (E_{p2}).

Table 1: The CO_2 emissions factors of conventional energy.

	Coal ($KgCO_2/GJ$)	Natural gas ($KgCO_2/GJ$)	Electricity ($KgCO_2/kWh$)	Gasoline ($KgCO_2/GJ$)
CO_2 emission coefficients	110.08	56.10	1.15	69.30

3. Case Study

3.1. Study Area. As Beijing is in its fast process of urbanization, community construction turns into a key element of the city renovation. This paper selects a typical high-quality community in Beijing as the case study. The community covers an area of $8.2 \times 10^3\,m^2$ with a construction area of $3.0 \times 10^5\,m^2$ and a living area of $9.0 \times 10^4\,m^2$. The community has 1630 households and a permanent population of 3100, with a green space of more than $2500\,m^2$ and a greening rate of 30%. The community has carried out the garbage classification since 2004. So far, the capacity of the kitchen waste disposal equipment that came into use has reached 20 kg per day. The power consumption is 2.24×10^5 kWh per month, and water consumption is about $1.63 \times 10^4\,m^3$ per month.

3.2. Data Analysis. CO_2 emission factors of primary energy are based on the CO_2 content of the fuels and the type of energy, which are elaborated in IPCC [60]. CO_2 emissions factors of electricity are based on coal factors but corrected by standard coal consumption of power supply (standard coal consumption 356 g/kWh, the average value in China [61]). CO_2 emissions factors for renewable energy are considered to be zero. The CO_2 emissions factors of energy are shown in Table 1. Other CO_2 emission factors of consumption goods can be referred to the embodied greenhouse gas emission database [62].

In this study, direct CO_2 emissions from the consumption of electricity and heating are not considered. The energy inputs for the production of electricity and district heating are estimated as the final consumption of energy production; that is, all emissions caused by energy production are specified for each of the fuel inputs [56].

The consumption data are developed based on the survey carried out in the community. Based on the previous studies engaged to classify the sectoral composition of consumption [48, 49, 63], we aggregate the community consumption in the database into the same expenditure framework, of which 8 emission categories include food, clothing and footwear, household appliances and services, health care, transport and communication, education and recreation, building, and miscellaneous goods, as listed in Table 2.

4. Results

4.1. Comparison of Tier 1, Tier 2, and Tier 3 CO_2 Emissions. The results show that the first 2 tiers defined by the current most carbon footprint protocols only occupy a small fraction of the total supply chain (Tier 3). Direct emissions from the community are only 1.58% of the total emissions, and on average only 11.46% of Tier3 are captured by Tier 2. The major carbon source is the total supply chain emissions embodied in the consumption of goods and activities, which is called Tier 3. Thus reduction emphasis should be put on Tier 3. From this aspect we can see that a large quantity of CO_2 emissions may be underestimated according to the current estimation protocols.

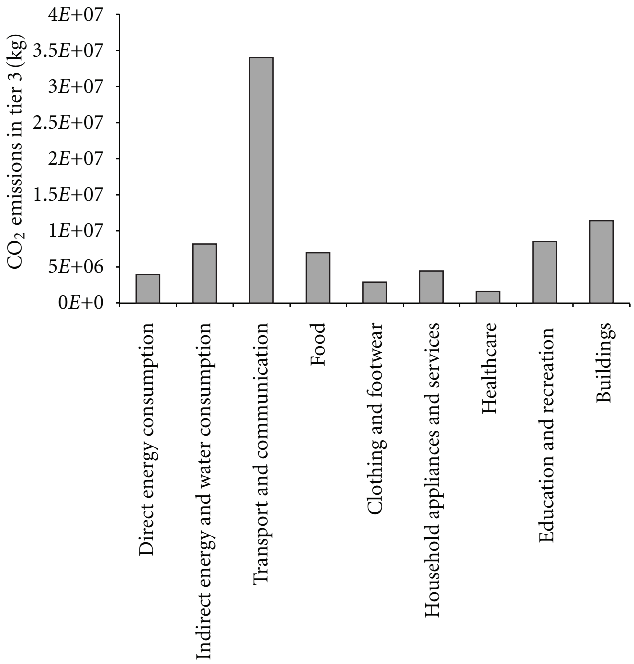

Figure 1: Total CO_2 emissions in Tier 3.

4.2. CO_2 Emissions Structure. For the total CO_2 emissions, which are defined as Tier 3, the top 3 emission items are transport and communication (41.36%), buildings (14.11%), and education and recreation (10.41%), as shown in Figure 1. Income is an important factor for CO_2 emission. In a typical high-quality community of Beijing, residents enjoy a high-standard life and prefer more convenient and faster communication tools. Thus more private cars and advanced communication tools are needed, which add to the total emissions.

The buildings consume a large amount of materials, equipment, energy, and manpower at the stages of construction, fitment, outdoor facility construction, transportation, operation, waste treatment, property management, demolition, and disposal [64]. Due to a lack of data, only the main material consumption is considered in this study. Although this part occupies 14.11% of the total CO_2 emission, it is still smaller than the real value.

Energy consumption tends to increase along with income rise, which is confirmed by numerous studies [65, 66]. Thus, the main CO_2 emissions are from goods purchasing.

Table 2: Consumption categories of the community.

No.	Items	Contents
1	Food	Miscellaneous food products, beverages, and tobacco products.
2	Clothing and footwear	Miscellaneous textile products, leather footwear.
3	Household appliances and services	Electrical appliances (television, computer, and other electrical machinery). Furniture and fixtures, wood products, and kitchen appliances.
4	Healthcare	Cosmetics, medical and health services, and other services.
5	Transport and communication	Communication equipments, ships and boats, railway, motor vehicles, bicycles, other transportation ways, and other transport services.
6	Education and recreation	Paper, paper products and newspapers, printing publishing and similar activities, and education and research.
7	Buildings	Residence and public buildings.
8	Misc goods and service	Trade, banking, insurance, and so forth.
9	Direct energy consumption	Natural gas, gasoline, diesel oil, and jet kerosene.
10	Indirect energy and water consumption	Electricity, heat, and water.

The expenditure of health care is the smallest, which is mainly due to the age structure present in this community.

4.3. Comparison with Nanjing Community. There is a previous study on the typical community of Nanjing-Zhujiang Road Community (termed as Site A) [67]. Per capita CO_2 emissions of Site A from electricity, natural gas, and petrol consumptions are 1144.5 kg, 48.7 kg, and 540.1 kg, while in our case are 974.19 kg, 374.19 kg, and 893.55 kg, respectively. CO_2 emission from electricity of Beijing case is 14.88% lower than that of Site A. The younger residents in Beijing community have a better sense of energy conservation and usually prefer energy saving appliances. The CO_2 emission from natural gas of Beijing case is nearly seven times higher than that of Site A because space heating in northern China contributes the most while people do not have heating services in southern China like Nanjing. Meanwhile, the CO_2 emissions from petrol consumption of Beijing case are 65.44% higher than that of Site A due to longer distance between working place and home in Beijing compared to Nanjing. Particularly, our case considers the total emissions embodied in the supply chain, which is often significantly underestimated by the previous studies.

5. Conclusions

In this paper, a new carbon accounting framework, that is, three-tier accounting method, was established to estimate the total embodied CO_2 emissions of urban community. The carbon emissions and the mitigation potential were quantified according to the proposed accounting framework. From the results we can obtain that in the concerned community only 11.46% of Tier 3 are captured by Tier 2. The major carbon source is the total supply chain emissions embodied in the consumption of goods and activities. The results also indicated that for the total CO_2 emissions, the top 3 emission items are transport and communication (41.36%), buildings (14.11%), and education and recreation (10.41%).

As can be seen, the mitigation emphases should be placed on Tier 3. Two major suggestions are thereby provided to realize the optimal resource allocation and further promotion for such communities. One is that we should strengthen the promotion of energy-efficient or green building and pay more attention to the renewable energy appliances such as solar energy water heater. The architectural of the houses should also be improved to reduce energy consumption of lightning and space heating. On the other hand, due to public transportation, the reconstruction of the urban public transportation is needed to reduce CO_2 emissions caused by the huge growth of private car ownership.

Acknowledgments

This study was supported by the Key Program of National Natural Science Foundation (no. 50939001), National Science Foundation for Innovative Research Group (no. 51121003), National Natural Science Foundation (no. 41271543), and Program for New Century Excellent Talents in University (NCET-09-0226). The authors are especially grateful for the financial support from Beijing Development Area Co. Ltd.

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The Scientific World Journal
Volume 2012, Article ID 862021, 7 pages
doi:10.1100/2012/862021

The ScientificWorldJOURNAL

Research Article

Nonrenewable Energy Cost and Greenhouse Gas Emissions of a "Pig-Biogas-Fish" System in China

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Received 27 August 2012; Accepted 26 September 2012

Academic Editors: B. Chen and Z.-M. Chen

The purpose of this study is to assess the energy savings and emission reductions of the present rural biogas system in China. The life cycle assessment (LCA) method is used to analyze a "pig-biogas-fish" system in Jingzhou, Hubei Province, China. The nonrenewable energy cost and the greenhouse gas (GHG) emissions of the system, including the pigsty, the biogas digester, and the fishpond, are taken into account. The border definition is standardized because of the utilization of the database in this paper. The results indicate that the nonrenewable energy consumption intensity of the "pig-biogas-fish" system is 0.60 MJ/MJ and the equivalent CO_2 emission intensity is 0.05 kg CO_2-eq/MJ. Compared with the conventional animal husbandry system, the "pig-biogas-fish" system shows high renewability and GHG reduction benefit, which indicates that the system is a scientific and environmentally friendly chain combining energy and ecology.

1. Introduction

Nowadays resources and environment have been the two focus of attention [1–3]. As a developing country, 60% population of which are peasants, China always takes development of economy and ecology of the rural area as one of the most important works [4]. To propel the sustainable development of the rural economy and to promote the continuous improvement of ecological environment, the Chinese government has long promoted biogas construction and has given it policy preferences, financial support, and technology inputs [5]. However, the biogas system is an energy conversion process, which will necessarily consume nonrenewable energy and discharge greenhouse gas (GHG) [6]. So it is meaningful to study the present rural biogas system over its entire life cycle.

The International Standardization Organization (ISO) defines life cycle assessment (LCA) as the following: "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [7]. Based on research experiences of other scholars and from our early studies [8–12], LCA can offer a comprehensive way to assess the energy consumption and greenhouse gas emissions of the given systems.

Several researchers have analyzed typical biogas systems using the LCA method. Some focused on the biogas technologies designed in laboratory [13, 14], and some focused on the biogas engineering itself [15, 16]. Patterson et al. [17] provided an assessment of biogas systems on a regional scale in the UK that can provide guidance on infrastructure development decisions; Martin et al. [18] utilized a life cycle approach to present the environmental impacts of the integration of biogas and ethanol processes; Wei et al. [19] assessed the efficiency and sustainability of the "Four in One" ecological economic system for peach production system in Beijing by life cycle energy analysis; Wang et al. [20] calculated and evaluated the energy conservation and the emission reductions of the rural household biogas project in China by establishing the LCA method. In these previous researches, when setting the system boundary, human factors

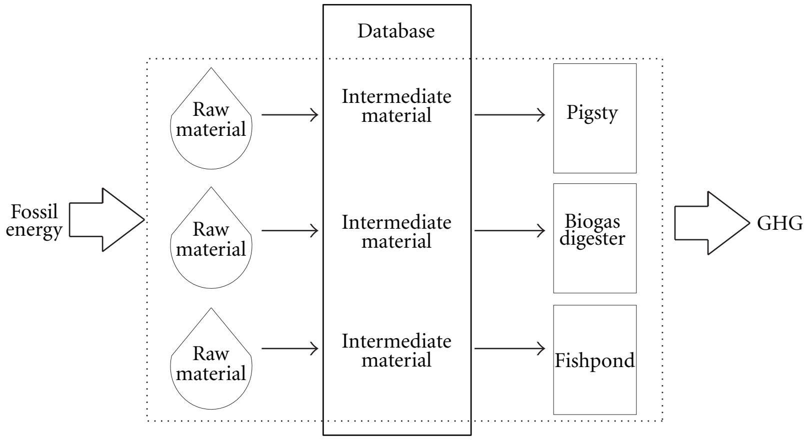

Figure 1: The boundary of the “pig-biogas-fish” system.

play a significant role. For a system, different researchers may get absolutely different results because of different boundary definition. For example, some researchers take transportation processes into account [21, 22], while some others do not [23], so the comparability of their data disappears. In this paper, the Chinese National Economy System Ecological Elements Database established by Zhou [24] is used for the calculation of the relevant ecological elements. Based on the system input and output of the simulation method, the Chinese National Economy System Ecological Elements Database is built in view of energy consumption, greenhouse gas emissions, and other key factors affecting the environment. Because of the certainty of the defining of the boundary in the database, the border definition is simplified and standardized. LCA is used to analyze a chosen rural household “pig-biogas-fish” system in the Zhongzhouzi fishery, Jingzhou Hubei Province in this research. Besides the biogas link, the upstream pigsty link, and, the downstream fishpond link are taken into account as a system, as showed in Figure 1. Also, the nonrenewable energy cost and the GHG emissions of this total system are calculated and compared to those of the conventional animal husbandry system.

2. Materials and Methods

2.1. Model of the “Pig-Biogas-Fish” System. The “pig-biogas-fish” system is a key unit to combine clean energy production and animal husbandry in China [25], and it works as follows: through raising pigs, farmers put the pig manure into the digester as the fermentation crude to product biogas for everyday lighting and cooking. Meanwhile, the biogas slurry and residue can be used as a base fertilizer and top dressing for the fishpond, as showed in Figure 2. The data of the “pig-biogas-fish” system in this study is provided by the survey of the Zhongzhouzi fishery, which is organized by the authors. The “pig-biogas-fish” system covers an area of about 5320 m^2, and it is designed with an operational life of 20 years. Below the elements of each link are described and analyzed separately, and the main consideration is the

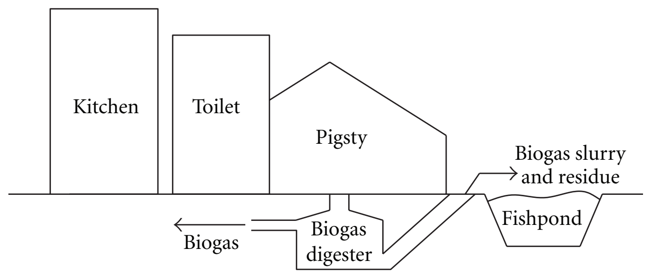

Figure 2: A schematic diagram of the “pig-biogas-fish” system.

productions in the construction, the operation, and the maintenance phases. One year is chosen as the time span for this study.

The pigsty covers an area of 20 m^2, and its construction investment is 2,000 Yuan, including cement, lime, hollow bricks, steel, and so forth. The main consumption in the daily operation of the pigsty is feed, vaccines, insect repellent, medicine, and disinfectant. The statistics show that on average a pig needs 363 kg of feed to grow to 100 kg, and each year it consumes about 6 g of drugs, such as the vaccine and the insect repellent. The pigsty needs to be disinfected at regular intervals.

This system includes an 8 m^3 biogas pool, with a cylindrical type. Its area is not considered. Its construction materials consist of 500 grade cement, fine sand, pebble, and a plastic discharge pipe 16 cm in diameter and 1.8 m in length, a plastic discharge pipe 20 cm in diameter and 0.8 m in length, a feed pipe 22 cm in diameter and 1.2 m in length, and an 8 m^3 steel mold.

The fishpond is excavated on the base of a natural small lake, covering an area of 5300 m^2. The main consideration is the investment in the fishpond operation and maintenance phases, and the investment in construction is ignored in this study. In the fish farming process, lime is needed regularly to disinfect the pond and bleach is used to prevent fish diseases. Beside biogas manure, nitrogen and phosphate fertilizer is applied to the fishpond for promoting the growth of aquatic plants. A certain amount of concentrated feed is also needed to ensure production.

Table 1: The output of the "pig-biogas-fish" system.

Outputs	Energy (MJ/yr)	Percentage (%)
Pig	$9.80E + 03$	8.65
Biogas	$1.00E + 04$	8.87
Fish	$9.34E + 04$	82.48
Total	$1.13E + 05$	100.00

The pigsty in this "pig-biogas-fish" system has an annual output of 8 pigs, with an average of 125 kg per head. This system produces 400 m^3 of biogas each year. The annual output of the fishpond is 2 kg/m^2. Table 1 is the statistical result of the energy content in the outputs for the system.

2.2. Model of the Conventional Animal Husbandry System. The conventional animal husbandry system consists of a pigsty with an area of 20 m^2 and a fishpond covering an area of 5300 m^2. In this paper, the model of the conventional animal husbandry system is set up based on the "pig-biogas-fish" system introduced above. The conventional animal husbandry system covers an area of about 5320 m^2, and its operational life is calculated as 20 years. In the conventional animal husbandry system, coal is used for everyday lighting and cooking, the energy of which is equal to the energy of the biogas produced in the "pig-biogas-fish" system. Without biogas manure, the qualities of the nitrogen and phosphate fertilizer applied to the fishpond in the conventional system, respectively, are 9 times more than those of the "pig-biogas-fish" system. The detailed inventories of the two systems are analyzed later in this paper.

2.3. Nonrenewable Energy Cost. To analyze the nonrenewable energy consumption of the system, we use the life cycle embodied energy method, an important type of the energy analysis methods [29–32]. Reister [33] has proposed energy intensity to quantify the energy embodied in goods, similar to energy conversion rate. However, his concept does not identify the renewable energy compound and the nonrenewable energy compound of the energy consumption. Therefore, FE is defined in this paper to show how much nonrenewable energy is used directly and indirectly in the whole process, including the system establishment, operation, and maintenance. And FE can be calculated as

$$\mathrm{FE} = \sum \mathrm{FE}_i = \sum \mathrm{Input}_i \times C_i, \quad (1)$$

where FE_i denotes the nonrenewable energy used directly and indirectly in the production of the ith input, Input_i, to the entire process of the biogas system. To calculate the proportion of the unit primary nonrenewable energy used directly and indirectly in the production or preparation of the ith input, C_i is defined as the nonrenewable energy intensity coefficient of the ith input. Such coefficients in this research are valued based on the Chinese National Economy System Ecological Elements Database. Therefore, this formula can calculate the nonrenewable energy cost implicit in the background of the system.

In order to quantify and evaluate the renewability of the system, it is appropriate to use nonrenewable energy investment in energy delivered (FEIED) [34, 35] as demonstrated below:

$$\mathrm{FEIED} = \frac{\mathrm{FE}}{E_{\mathrm{out}}}, \quad (2)$$

where E_{out} is the energy content of the outputs of the system. FEIED is a proportional relationship between the nonrenewable energy consumed by the system and the nonrenewable energy replaced by the system. FEIED > 1 indicates a nonrenewable process in which more energy is consumed than energy delivered, while FEIED < 1 indicates a renewable process in which more energy is delivered than energy invested. Also, the smaller the FEIED is, the higher the renewability is.

2.4. GHG Emissions. Generally the GHG emissions of a product consist of two parts. One is the direct emissions part monitored by local department, and the other is the indirect emissions' part caused by inputs during the process [36]. GHG emission intensity (EI) is defined as the amount of GHG generated by one unit output energy of the system, expressed as

$$\mathrm{EI} = \frac{\mathrm{GE}}{E_{\mathrm{out}}}, \quad (3)$$

where GE is the GHG emissions of the system during its entire life cycle, including the direct and indirect emissions.

In this paper, input-output (I-O) analysis and process analysis are combined to compute the GHG emissions of the "pig-biogas-fish" system. The GHG emissions linked to land use are also considered. For the "pig-biogas-fish" system, its direct GHG emissions mainly include three parts: (1) CH_4 released into the air by swine enteric fermentation; (2) N_2O produced by fermentation in the biogas digester and CO_2 generated by the biogas combustion; (3) CO_2 and CH_4 released into the air by the fishpond (considered as the wetland). The direct emissions are calculated according to the statistical data. Furthermore, in the process of its construction, operation, and maintenance, the "pig-biogas-fish" system consumes some products, produced by other systems, and a certain amount of GHG is emitted during the production processes; these emissions derived from outside the biogas system are the indirect GHG emissions. Similarly, the indirect GHG emissions ($\mathrm{GE}_{\mathrm{in}}$) associated with FE can be calculated as

$$\mathrm{GE}_{\mathrm{in}} = \sum \mathrm{GE}_i = \sum \mathrm{Input}_i \times G_i, \quad (4)$$

where GE_i denotes the GHG emissions in the production of ith inputs and G_i is defined as the GHG intensity coefficient of the ith inputs, valued based on the Chinese National Economy System Ecological Elements Database.

Limited to the national conditions and statistics, this study mainly considers three greenhouse gases, CO_2, CH_4, and N_2O. And in accordance with the standard of 100-year scaleglobal warming potential, CH and N_2O are equivalent to CO_2 as 23 g/g and 296 g/g [37], respectively.

Table 2: FE cost and GE_{in} emissions of the "pig-biogas-fish" system.

Links	Materials	Quantity	Unit	C_i^* (MJ/unit)	G_i^* (kg CO_2-eq/unit)	FE (MJ/yr)	GE_{in} (kg CO_2-eq/yr)
Pigsty	Cement	$1.75E+01$	kg/yr	6.36	0.53	$1.11E+02$	$9.28E+00$
	Lime	$1.25E+01$	kg/yr	4.94	0.79	$6.18E+01$	$9.88E+00$
	Hollow bricks	$1.50E+00$	kg/yr	6.36	0.53	$9.54E+00$	$7.95E-01$
	Steel	$2.63E+00$	kg/yr	64.5	2.03	$1.69E+02$	$5.33E+00$
	Feed	$2.90E+03$	kg/yr	4.64	0.52	$1.35E+04$	$1.51E+03$
	Drugs	$4.80E-02$	kg/yr	134	3.00	$6.43E+00$	$1.44E-01$
	Disinfectant	$4.00E-01$	kg/yr	46.9	1.68	$1.88E+01$	$6.72E-01$
	Water	$5.66E+01$	ton/yr	34.6	0.81	$1.96E+03$	$4.58E+01$
	Electricity	$6.40E+01$	kWh/yr	135	2.82	$8.64E+03$	$1.80E+02$
Biogas	Cement	$4.50E+01$	kg/yr	6.36	0.53	$2.86E+02$	$2.39E+01$
	Sand and pebble	$3.13E+00$	\$/yr	2.98	0.00	$9.33E+00$	$0.00E+00$
	Plastic pipe	$4.00E+00$	kg/yr	108	2.99	$4.32E+02$	$1.20E+01$
	Steel mold	$1.25E+02$	kg/yr	173	2.24	$2.16E+04$	$2.80E+02$
Fishpond	Lime	$4.80E+02$	kg/yr	4.94	0.78	$2.37E+03$	$3.74E+02$
	Bleach	$3.20E+00$	kg/yr	46.9	1.68	$1.50E+02$	$5.38E+00$
	Feed	$2.50E+02$	kg/yr	4.64	0.52	$1.16E+03$	$1.30E+02$
	Aerator	$1.25E+00$	\$/yr	32.4	2.24	$4.05E+01$	$2.80E+00$
	Nitrogen	$2.00E+02$	kg/yr	67.8	1.64	$1.36E+04$	$3.28E+02$
	Phosphate	$1.10E+02$	kg/yr	36.2	1.05	$3.98E+03$	$1.16E+02$
Total						$6.80E+04$	$3.03E+03$

* Zhou [24].

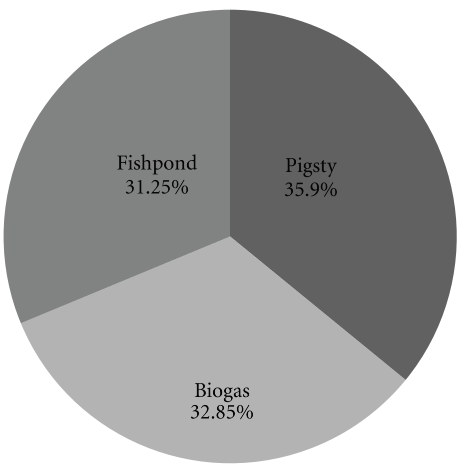

Figure 3: NE cost fractions for the "pig-biogas-fish" system.

Table 3: Direct GHG emissions of the "pig-biogas-fish" system.

Direct GHG	CO_2 (kg/yr)	CH_4 (kg/yr)	N_2O (kg/yr)
Pigsty		12.00*	
Biogas	830.50**		1.14***
Fishpond****	646.88	45.36	

* IPCC [26].
** Biogas composition is considered as 70% CH_4 and 30% CO_2.
*** Ma and Nan [27].
**** Xing et al. [28].

Table 4: GE of the "pig-biogas-fish" system.

	Direct GHG (kg CO_2-eq/yr)	GE_{in} (kg CO_2-eq/yr)	GE (kg CO_2-eq/yr)
Pigsty	$2.76E+02$	$1.76E+03$	$2.04E+03$
Biogas	$1.17E+03$	$3.16E+02$	$1.48E+03$
Fishpond	$1.69E+03$	$9.56E+02$	$2.65E+03$
Total	$3.13E+03$	$3.03E+03$	$6.17E+03$
Ratio	50.82%	49.18%	100.00%

3. Results and Discussions

3.1. Calculation of the Nonrenewable Energy Cost of the "Pig-Biogas-Fish" System. The nonrenewable energy consumption of the "pig-biogas-fish" system is shown in Table 2. The total FE cost for the system is $6.80E + 04$ MJ/yr. As listed in Table 1, the E_{out} of the system is $1.13E + 05$ MJ/yr. Thus FEIED of the "pig-biogas-fish" system is evaluated as 0.60 MJ/MJ, less than 1, and it reveals that this system has renewability. Analysis of the FE cost of the system shows that the difference between the pigsty link (35.90%), the biogas link (32.85%), and the fishpond link (31.25%) is not significant (see Figure 3), and the fishpond fraction is the smallest among the three. In addition, Table 1 shows that the fishpond accounts for the largest proportion of energy outputs. So the fishpond has the highest economic benefit. This also demonstrates that the fishpond has a favorable impact on the renewability of the "pig-biogas-fish" system.

TABLE 5: FE cost and GE_{in} emissions of the conventional animal husbandry system.

	Materials	Quantity	Unit	C_i^* (MJ/unit)	G_i^* (kg CO_2-eq/unit)	FE (MJ/yr)	GE_{in} (kg CO_2-eq/yr)
Pigsty	Cement	$1.75E+01$	kg/yr	6.36	0.53	$1.11E+02$	$9.28E+00$
	Lime	$1.25E+01$	kg/yr	4.94	0.79	$6.18E+01$	$9.88E+00$
	Hollow bricks	$1.50E+00$	kg/yr	6.36	0.53	$9.54E+00$	$7.95E-01$
	Steel	$2.63E+00$	kg/yr	64.5	2.03	$1.69E+02$	$5.33E+00$
	Feed	$2.90E+03$	kg/yr	4.64	0.52	$1.35E+04$	$1.51E+03$
	Drugs	$4.80E-02$	kg/yr	134	3.00	$6.43E+00$	$1.44E-01$
	Disinfectant	$4.00E-01$	kg/yr	46.9	1.68	$1.88E+01$	$6.72E-01$
	Water	$5.66E+01$	ton/yr	34.6	0.81	$1.96E+03$	$4.58E+01$
	Electricity	$6.40E+01$	kWh/yr	135	2.82	$8.64E+03$	$1.80E+02$
Farmers	Coal	$2.86E+02$	kg/yr	29.56	3.2	$8.44E+03$	$9.14E+02$
Fishpond	Lime	$4.80E+02$	kg/yr	4.94	0.78	$2.37E+03$	$3.74E+02$
	Bleach	$3.20E+00$	kg/yr	46.9	1.68	$1.50E+02$	$5.38E+00$
	Feed	$2.50E+02$	kg/yr	4.64	0.52	$1.16E+03$	$1.30E+02$
	Aerator	$1.25E+00$	\$/yr	32.4	2.24	$4.05E+01$	$2.80E+00$
	Nitrogen	$2.00E+03$	kg/yr	67.8	1.64	$1.36E+05$	$3.28E+03$
	Phosphate	$1.10E+03$	kg/yr	36.2	1.05	$3.98E+04$	$1.16E+03$
Total						$2.12E+05$	$7.62E+03$

* Zhou [24].

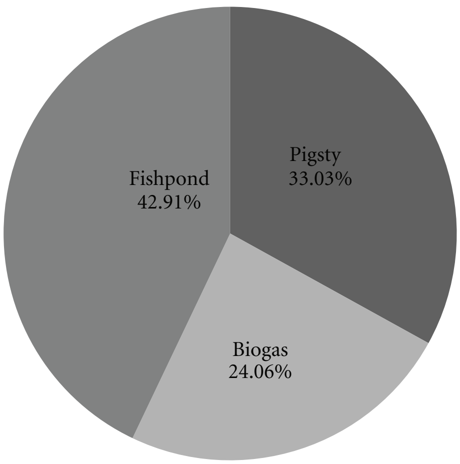

FIGURE 4: GM fractions for the "pig-biogas-fish" system.

TABLE 6: GE of the conventional animal husbandry system.

	Direct GHG (kg CO_2-eq/yr)	GE_{in} (kg CO_2-eq/yr)	GE (kg CO_2-eq/yr)
Pigsty	$2.76E+02$	$1.76E+03$	$2.04E+03$
Farmers	$0.00E+00$	$9.14E+02$	$9.14E+02$
Fishpond	$1.69E+03$	$4.95E+03$	$6.64E+03$
Total	$1.97E+03$	$7.62E+03$	$9.59E+03$
Ratio	20.50%	79.50%	100.00%

3.2. Calculation of the GHG Emissions of the "Pig-Biogas-Fish" System. The indirect and direct GHG emissions of the "pig-biogas-fish" system are showed separately in Tables 2 and 3, thus the total GHG emissions can be obtained (see Table 4). The total GHG emissions for the system is summed up to be $6.17E+03$ kg CO_2-eq/yr. Then, EI of the "pig-biogas-fish"system is evaluated as 0.05 kg CO_2-eq/MJ.

Analysis of the GE of the system shows that the fishpond link (42.91%) is the largest contributor, followed by the pigsty link (33.03%), and the biogas link (24.06%) is the smallest one as showed in Figure 4. The GE_{in} emission inventory of the fishpond link is showed in Table 2. Because biogas manure cannot meet the need of fish farming, nitrogen and phosphate fertilizers are applied to the fishpond. These two materials account for a large proportion of the total GHG emission of the fishpond, at 16.76%. Therefore, if the nutrient content of the biogas manure could be improved by biochemical methods, the amount of these two fertilizers could be reduced and the GHG emissions would also be reduced.

3.3. Comparison with the Conventional Animal Husbandry System. The FE cost of the conventional animal husbandry system is $2.12E+05$ MJ/yr, showed in Table 5, the E_{out} of the system is $1.03E+05$ MJ/yr, and the GE of the system is summed up to be $9.59E+03$ kg CO_2-eq/yr (see Table 6). Therefore, FEIED of the conventional animal husbandry system is 2.06 MJ/MJ, greater than 1, revealing that this system is a nonrenewable system, and EI of the plant is 0.09 kg CO_2-eq/MJ. Compared with the conventional animal husbandry system, the "pig-biogas-fish" system has higher renewability because its FEIED is smaller, and the "pig-biogas-fish" system also has a higher GHG reduction benefit because its EI is smaller. This is mainly because the "pig-biogas-fish" system makes use of waste feces to provide families with the energy for everyday needs. It can therefore reduce the quantity of coal, biomass, fertilizer, and other combustions, and thus the nonrenewable energy cost and the GHG emissions are reduced, also.

At present, the national average FEIED and EI of thermal power plants are 2.64 MJ/MJ and 0.22 kg CO_2-eq/MJ, respectively [23]. The coal power system therefore tends to consume 3.4 times more FE and 3.4 times more GHG emissions than the "pig-biogas-fish" system per unit energy output to the society.

4. Concluding Remarks

The system of "pig-biogas-fish" in Hubei Province, China, is analyzed by LCA in this paper. For this system, the renewability indicator FEIED, defined as nonrenewable energy investment in energy delivered, is estimated as 0.60 MJ/MJ, which shows that it has renewability. Its GHG emission intensity, EI, is calculated as 0.05 kg CO_2-eq/MJ. Compared with the conventional animal husbandry system which consists of a pigsty and a fishpond, the "pig-biogas-fish" system has an advantage in renewability and GHG reductions.

(1) FEIED of the "pig-biogas-fish" system is less than 1 and far less than that of thermal power plants in China. It indicates that the "pig-biogas-fish" system has renewability, and the fishpond link plays an important role as the analysis shows above.

(2) EI of the "pig-biogas-fish" system is 1/4 of that of the present domestic coal power system, which means that as these two systems output the equal energy, the "pig-biogas-fish" system can reduce GHG emissions by 75% relative thermal power plants. Thus the rural biogas system has a positive impact on reaching the emission reduction target of China.

(3) The rural biogas system, on the one hand, can meet the everyday needs of production and living for the famers, and on the other hand, it can reduce environmental pollution and make full use of biomass resources. So it is a scientific and environmentally friendly chain combining energy and ecology, in line with national conditions of China.

Acknowledgments

This study has been supported by the Fundamental Research Funds for the Central Universities (no. 2012QN175), the National Natural Science Foundation of China (no. 51021065), the Twelfth Five-year Plan of the National Key Technology R&D Program (no. 2011BAD15B05-03), and the National High Technology R&D Program 863 (no. 2012AA051803). Wu also would like to thank Miss Heather Ramsay for her generous help and comments.

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The Scientific World Journal
Volume 2012, Article ID 907685, 8 pages
doi:10.1100/2012/907685

The ScientificWorldJOURNAL

Research Article

CO_2 Mitigation Measures of Power Sector and Its Integrated Optimization in China

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Received 7 September 2012; Accepted 15 October 2012

Academic Editors: D. F. Cheddie and H. Choi

Power sector is responsible for about 40% of the total CO_2 emissions in the world and plays a leading role in climate change mitigation. In this study, measures that lower CO_2 emissions from the supply side, demand side, and power grid are discussed, based on which, an integrated optimization model of CO_2 mitigation (IOCM) is proposed. Virtual energy, referring to energy saving capacity in both demand side and the power grid, together with conventional energy in supply side, is unified planning for IOCM. Consequently, the optimal plan of energy distribution, considering both economic benefits and mitigation benefits, is figured out through the application of IOCM. The results indicate that development of demand side management (DSM) and smart grid can make great contributions to CO_2 mitigation of power sector in China by reducing the CO_2 emissions by 10.02% and 12.59%, respectively, in 2015, and in 2020.

1. Introduction

Global climate change is a salient challenge in achieving sustainable development of human society. CO_2 emissions and other greenhouse gas are the leading cause of global warming. If we do not take measures, CO_2 emissions related to fuel energy will be doubled in 2050. As per statistical results of International Energy Agency (IEA), power sector is responsible for about 40% of the total CO_2 emissions [1]. Consequently, CO_2 mitigation in power sector is of great significance in achieving global mitigation goal.

Power sector can be divided into supply side, demand side and power grid according to transmission process. The CO_2 emissions of power sector are concentrated in supply side, where fossil fuels burn. Unreasonable utilization in demand side and losses in power grid would increase energy consumption in supply side, which also indirectly contributes more CO_2 emissions. CO_2 mitigation measures adopted in supply side could be divided into three categories [2–8]: (a) improving conversion efficiency of fossil energy and lower energy intensity; (b) developing nonfossil energy like renewable energy and nuclear energy and adjust energy mix; (c) developing carbon capture and storage (CCS) technologies. The most effective measure in CO_2 mitigation in demand side is to implement DSM, which improves utilization efficiency through incentive policies [9, 10]. The literature [11, 12] shows that DSM could reduce energy consumption by 5% to 15%. Power grid is not only a bridge connecting supply side and demand side physically, but also an important medium of achieving mitigation benefits of both sides. Besides, it provides support for large-scale applications of nonfossil energy (including nuclear energy, hydroelectric energy, and wind energy) [12]. With the development of smart grid and ultra-high voltage grid (UHV), losses decreased vastly. Thereby, power grid shows greater mitigation potential compared with other energy transmission methods. Based on current energy mix and generation technology, low-carbon power dispatch is an effective way to control CO_2 emissions in a short period of time [13, 14].

The current researches on CO_2 mitigation measures mainly focus on application of various mitigation techniques and macroinfluence of policies. However, researches on optimization of CO_2 mitigation from the point of whole power sector are still rare. Integrated resource planning (IRP) and integrated resource strategic planning (IRSP) minimize power supply through optimization on both demand and supply sides [15–18]. However, energy saving capacity of power grid is neglected. In this study, an optimization model IOCM, considering all mitigation potential of supply side, demand side, and the power grid, is proposed and applied to the power sector in China.

In Section 2, the status quo of CO_2 emissions of power sector is briefly represented. In Section 3, various measures on CO_2 mitigation are discussed. Then, the IOCM is proposed in Section 4, and the result of IOCM applied to power sector in China is analyzed in Section 5. Finally, conclusions are made in Section 6.

2. CO_2 Emissions of Power Sector in China

The major CO_2 emissions country in the world, China, officially pledged to reduce its CO_2 intensity by 40–45% from the 2005 level and increase the share of nonfossil energy in primary energy to 15% by 2020 [19]. CO_2 emissions from power sector reached 3294.7 million tonnes (Mt) in 2009, accounting for 48% in total emissions [1]. Consequently, CO_2 mitigation in power sector is of great significance in achieving long-term mitigation goal in China and even making contribution to global mitigation.

China is at critical stage of industrialization and urbanization, and the demand for electricity increases rapidly. Electricity generation reached 4721.7 terawatt hours (TWh) in China in 2011, ranking in the second place in the world. Meanwhile, primary fuel mix is dominated by coal in China. Electricity from coal-fired power plants accounts for approximately 80% of the total electricity generation [20]. Therefore, the demand for electricity in China was the largest driver of the rise in emissions. As per statistical results of IEA, the CO_2 emissions from electricity and heat production increased by 210% from 1,072.0 to 3,324.3 Mt between 1995 and 2009 [1], as shown in Figure 1.

The primary responsibility of power sector is to ensure sufficient, safe, and stable power supply. Development is still the primary task, so effective measures should be taken to reduce CO_2 emission, under the premise of meeting the power demand of economic and social development. Among the period of the "Eleventh Five-Year Plan" (from 2006 to 2010), measures to develop nonfossil energy, reduce coal consumption and line losses, and so forth, power sector has cut 1.74 billion tonnes of CO_2. The contribution ratio of various measures for CO_2 mitigation is displayed in Figure 2, among which measures to reduce coal consumption ranked at the top, up to 51% [21]. Although some achievements have been made concerning CO_2 mitigation, a comparatively big gap from the target still exists. Therefore, various measures for CO_2 mitigation should be promoted.

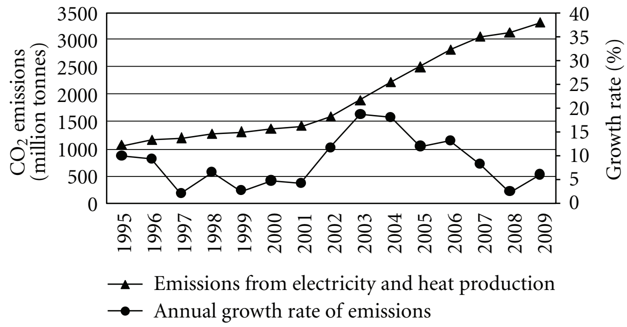

Figure 1: CO_2 emissions from electricity and heat production from 1995 to 2009 in China.

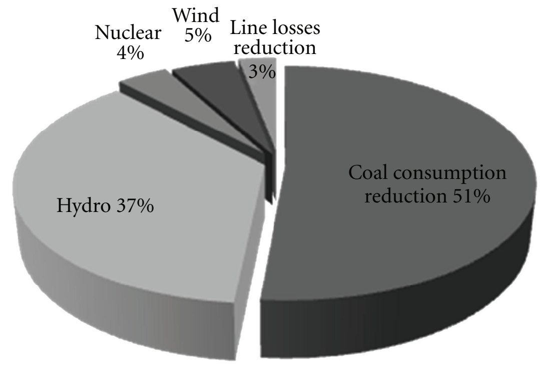

Figure 2: The contribution ratio of measures on CO_2 mitigation from 2006 to 2010.

3. CO_2 Mitigation Measures of Power Sector

3.1. CO_2 Mitigation Measures in Supply Side. Coal played a major role in supporting the growing electricity demand in China. Nearly all of the emissions growth from power generation has been derived from coal in the recent two decades, although the emissions performance of coal-fired power generation has improved significantly [1]. Based on the generation mix, the measures on CO_2 mitigation can be divided into three major categories.

3.1.1. Efficiency Improvement of Utilization of Fossil Energy. Efficiency improvement refers to the use of less amount of fossil fuel and CO_2 emission to produce the same amount of electricity by improving conversion efficiency. This measure is useful for China, where coal is the major energy resource and widely promoted in power sector, thereby, receiving extensive attention at present.

Replacement of backward units with advanced coal-fired generation units with large capacity and high efficiency is an important measure to improve the conversion efficiency. There also exist a number of small-sized, low efficiency coal-fired generation units in China. As a result, this measure still has great potential in more reduction. However, the potential for efficiency improvement and CO_2 mitigation will continuously decrease as the capacity increases. At this time, more high-efficient generation technologies should be developed like integrated gasification combined cycle and ultra super-critical power generation. In addition, efficiency improvement is expected to reduce CO_2 emissions for per kilowatt hour (kWh), but the total CO_2 emissions of power sector in China may still increase continuously as installed capacity has grown quickly in recent years.

3.1.2. Adjust Energy Mix. Replacement of coal with low-carbon fuel or energy with near-zero CO_2 emission, such as natural gas, renewable energy, and nuclear energy, to adjust energy mix is a significant measure for controlling CO_2 emissions in the process of power generation.

(1) Low-Carbon Fuel. CO_2 emission of each unit of electricity generated by natural gas is 50%~60% lower than that of traditional thermal power units [22]. Consequently, improvement of utilization ratio of low-carbon fuel like natural gas is a feasible measure of CO_2 mitigation. However, natural gas resource for generation in China is severely scarce, which contributes little to emission reduction. Thus, the key point to decide whether to put low-carbon fuel into wide use lies in the chance to get stable natural gas supply in low cost or get new gas resource at lower cost.

(2) Renewable Energy. Renewable power generation technologies mainly include hydropower, wind power, solar power, biomass power, ocean power, and geothermal power. Generally, most renewable power generation produces CO_2 during the process of manufacturing equipment and consumables, but no direct CO_2 emissions arise during power generation process. As a result, it can be seen as near-zero CO_2 emissions. According to factors regarding technologies and resources, renewable power generation can be developed properly and also serve as an important method of CO_2 reduction in electricity industry.

China has abundant hydropower resources that remain as the most developed renewable energy resources in the country. The technology of hydroelectricity is relatively mature, of which the installed capacity and generating capacity is the second largest method of power generation next to coal in China. However, large-sized hydropower plants exert some indirect negative impacts on the environment along with the vigorous development of hydropower. Wind energy resource in China is densely located in western, northern, and coastal areas, which is appropriate for centralized development. Similar to wind energy resource, solar energy resource is mainly in western and northern areas. With the development of solar technology, solar energy development is fastened in our country. Low in cost, biomass energy is developed rapidly but with problems in limited resource, collection of biomass, and equipment manufacture. So it should be developed, accordingly. Besides, renewable energy like geothermal energy and ocean energy has certain irreplaceable status in certain area, which leads to fast development in research.

However, the impact on grid stability must be taken into deep consideration, as the connected renewable energy may bring fluctuations into the grid. For instance, wind and sun energy bring along strong fluctuations on a daily and seasonal basis. When the proportion of wind energy is too large, it leads to strong fluctuations in power grid [23].

(3) Nuclear Power. Nuclear power, a relatively mature technology, is applied to electricity generation for the remarkable advantages of low operating costs and near-zero CO_2 emissions. However, it has also encountered barriers, which is mainly related to the public safety like nuclear weapons proliferation and waste management. Chinese technology on nuclear power also requires further development. After over 20 years of development, the basis of China's nuclear industry gradually formed. At present, nuclear power has entered a period of rapid development, and meanwhile the security is always on the primary position.

3.1.3. CCS Technologies. CCS is a process, in which CO_2 is separated from industrial or energy production chain, then transported to a storage location, and isolated from the atmosphere for a long period of time. It is widely recognized as an exceptional technology in global mitigation, because of its huge potential of an 85% to 90% reduction of CO_2 emissions in thermal power stations [24]. So far, CCS demonstration projects have been constructed in several thermal power stations of Beijing, Shanghai, and some other places. However, they are restricted to small-scale plants. Due to the high investment cost and large energy consumption of CCS under the current technology level, only small-scale projects can be implemented as future technical reserves of CO_2 mitigation. Since new CCS technology with low cost and energy consumption is the focus of future research, China should track related technical updates in order to meet the growing demand of CO_2 mitigation.

3.2. CO_2 Mitigation Measures in Demand Side. DSM, the most effective measures on mitigation in demand side, is a series of electricity management activities aiming at energy conservation and environmental protection, by optimizing the terminal power consumption mode and improving utilization efficiency. Thus, the power demand and CO_2 emissions in power industry decrease indirectly.

In China, the DSM has been explored and carried out since the 1990s. During 1991 to 1995, a number of DSM seminars lectured by international experts were organized in China. During 1996 to 2000, several DSM demonstration projects, such as the applications of peak-valley price, energy-saving lamps, were gradually developed, which accumulated experience for DSM. Especially since 2002, DSM has received extensive attention of the whole society due to the tense relationship between power supply and demand. Since then, DSM has entered a period of rapid development in China. New policies on DSM have been released by national and provincial governments, which play an optimistic role in implementing the orderly use of electricity, enhancing energy efficiency, and easing the contradiction between power supply and demand.

Drawing on advanced experience from foreign countries, DSM work can be expanded successfully through the following advices.

(1) Governments of all levels should play a leading role in creating a conducive environment for DSM.

(2) An effective incentive for stable financial support for carrying out DSM should be quickly set up.

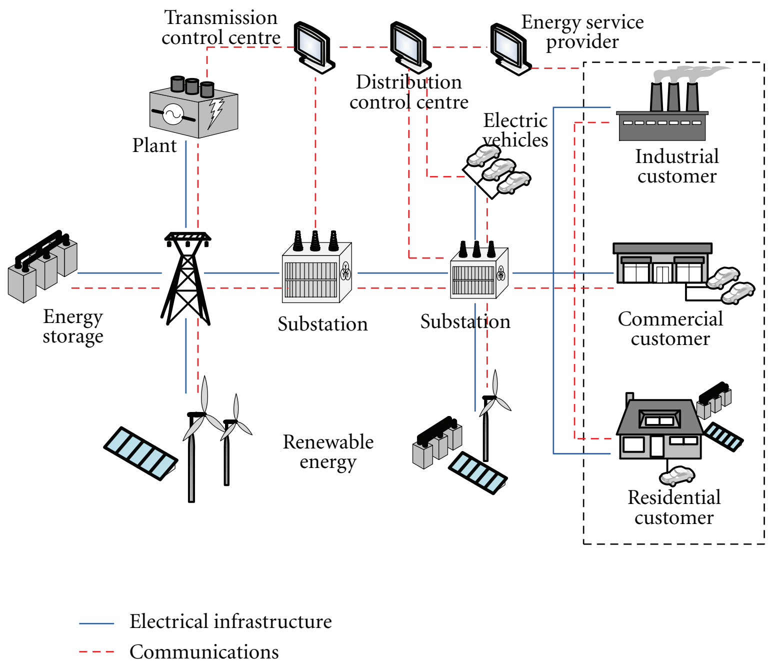

FIGURE 3: The smart grid chart.

(3) Electric power companies should play a dominant role in DSM extension and application.

(4) Energy-saving intermediary organizations can help to form a market mechanism of energy conservation.

3.3. CO_2 Mitigation Measures in Power Grid. Power grid is not only a bridge connecting supply side and demand side physically, but also an important medium of achieving mitigation benefits of both sides. The smart grid is considered as a way to reduce energy consumption, improve the electricity network efficiency, and manage renewable energy generation. Besides, it provides accesses for nonfossil energy to get into the grid, including nuclear power, hydropower, wind power and other near-zero emission energy. Briefly speaking, smart grid is an important mean to realize energy conservation and emission reduction, as well as the climate change mitigation.

Smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the electricity transmission from all generation sources to meet the varying electricity demands of end-users, as seen in Figure 3. The significance of the smart grid construction in the promotion of energy conservation and the development of low-carbon economy is as follows.

(1) Large-scale clean energy units are allowed to get connected into the grid speed up the development of clean energy promote the optimization, and adjustment of energy mix.

(2) Consumers are guided to arrange time duration of electricity consumption, cut down the peak load and the coal consumption in a reasonable manner.

(3) Line losses will decrease remarkably in transmission due to the applications of advanced technologies, including UHV, flexible transmission, low-carbon power dispatch, and distributed generation, as well as dual-direction interaction between consumers and the grid.

(4) Effective interaction between the grid and consumers will be achieved. The promotion of energy-saving technologies will improve the power consumption efficiency.

(5) Large-scale applications of electric vehicles will be promoted. Low-carbon economy will get improved and the mitigation benefits will be achieved.

State Grid Corporation is committed to building a strong smart grid in China, in which UHV power grid is taken as the backbone, and grids at all levels develop coordinately. Plans for a pilot smart grid were outlined in 2010, programming the extension deployment to 2030. Investments in the smart grids will have reached at least USD 96 billion by 2020 [25].

4. The Construction of IOCM

Since any single measure is far from the goal of CO_2 mitigation in power sector, all feasible options must be taken into consideration. In this section, equivalent virtual energy, consisting of the energy saving capacity in both demand side and the power grid, together with the conventional energy in supply side is unified planning for IOCM. Objective function of IOCM denotes the lowest cost and CO_2 emissions. Finally, the optimal plan of energy distribution, considering both economic benefits and mitigation benefits, can be figured out by multiobjective optimization calculations (Figure 4).

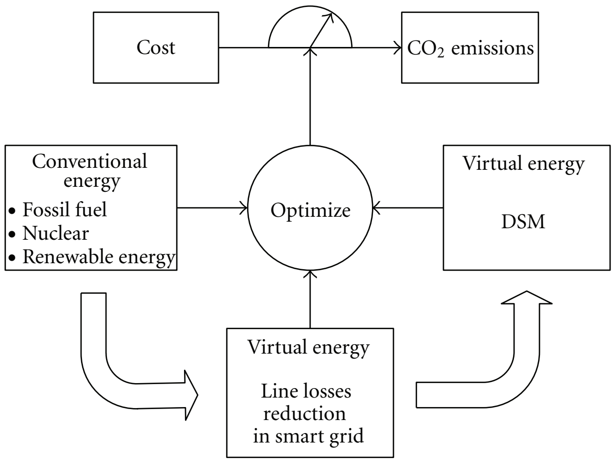

Figure 4: Schematic Diagram of IOCM.

Virtual energy in power grid works mainly through smart grid technologies, such as UHV, low-carbon power dispatch, and distributed generation, bringing less line loss. The energy, coming from line losses reduction, is regarded as the smart grid virtual energy (SGVE). Virtual energy in demand side works through DSM, mainly including energy-saving lamps (LVE), energy-saving motors (MVE), energy-saving transformers (TVE), frequency converter (FCVE), and efficient appliances (AVE). For instance, all DSM programs, aiming at promotion of energy-saving lamps, can be gathered up as LVE.

4.1. Objective Functions. The lowest-cost objective function denotes the minimum net present value of the total cost, when meeting the electricity demand. It can be expressed by

$$\min f_{\mathrm{COST}} = \sum_{y=1}^{Y} \left\{ \sum_{n=1}^{N} \left[\mathrm{ACI}_{yn} \left(C_{yn} - C_n^0 \right) + \mathrm{CO}_{yn} \cdot P_{yn} \cdot 8760 \right] \times \frac{1}{(1+r)^y} \right\}, \quad (1)$$

where y is the yth year of studied; Y is the total number of years studied; n is the nth type of energy source; N is the total types of energy source, including fossil fuel, nuclear, renewable energy and virtual energy; ACI_{yn} is the annual value of the investment cost of the nth type of energy per unit capacity in the yth year, China Yuan/kilowatt (CNY/kW); CO_{yn} is the operating cost of the nth type of energy per unit generation in the yth year, China Yuan/kilowatt hour (CNY/kWh); C_{yn} is the installed capacity of the nth type of energy in the yth year, kilowatt (kW); C_n^0 is the existing installed capacity of the nth type of energy, kW; P_{yn} is the average power generation output of the nth type of energy in the yth year, kW; r is the discount rate.

The lowest-emissions objective function denotes the lowest CO_2 emissions, when meeting the electricity demand. It can be expressed by

$$\min f_{\mathrm{CO}_2} = \sum_{y=1}^{Y} \sum_{n=1}^{N} P_{yn} \cdot 8760 \cdot \theta_{yn}, \quad (2)$$

where θ_{yn} is the CO_2 emissions coefficient of the nth type of energy in the yth year tonnes/kWh. Value of θ_{yn} decreases with the further efficiency improvement of utilization of fossil energy and wider applications of CCS technologies.

Optimal plans of energy distribution based on (1) and (2) are quite different. The optimal plan based on (1) contains a mass of low-cost energy, while that these based on (2) contains a mass of clear energy instead. However, contradict results in a certain extent, and the fuzzy multiobjective planning method is used here to solve this problem.

4.2. Constraint Conditions

(1) Electricity Demand Constraints. The electricity generation of both conventional and virtual energy is not less than the predicted electricity demand

$$\sum_{n=1}^{N} P_{yn} \cdot 8760 \geq E_y \quad (y = 1, 2, \ldots, Y), \quad (3)$$

where E_y is the predicted value of electricity demand in the yth year kWh.

(2) Peak Load Constraints. The total installed capacity of both conventional and virtual energy is not less than the sum of peak load and reserve capacity

$$\sum_{n=1}^{N} C_{yn} \geq (1 + R) \cdot D_y \quad (y = 1, 2, \ldots, Y), \quad (4)$$

where D_y is the predicted value of peak load in the yth year, kW; R is the coefficient of reserve capacity.

(3) Generation Output Constraint. The annual electricity generation of each type of energy cannot exceed its upper limit

$$P_{yn} \cdot 8760 \leq C_{yn} \cdot T_n \quad (n = 1, 2, \ldots, N;\ y = 1, 2, \ldots, Y), \quad (5)$$

where, T_n is the annual utilization hours of the nth type of energy, hour.

(4) Installed Capacity Constraints. Due to the technology, funds, policy, and other limits, the annual installed capacity of each type of energy has its upper limit which cannot be exceeded

$$C_{yn} \leq C_{yn}^{\max} \quad (n = 1, 2, \ldots, N;\ y = 1, 2, \ldots, Y), \quad (6)$$

where $C_{yn}^{\max}$ is the maximum allowable capacity of the nth type of energy in the yth year, kW.

TABLE 1: Power demand and installed capacity for each type of energy in TFP [20].

	Power demand		Installed capacity							
	Electricity consumption (TWh)	Peak load (GW)	Coal (GW)	Gas (GW)	Hydro (GW)	Nuclear (GW)	Wind (GW)	Solar (GW)	Biomass (GW)	Total (GW)
2015	6270	1040	933	30	325	43	100	2	3	1437
2020	8200	1377	1160	40	390	90	180	20	5	1885

TABLE 2: Main parameters in IOCM [17–20].

	Life (years)	Investment cost (CNY/kW)	CO_{yn} (CNY/KWh)	T_n (hours)	θ_{yn} (gram/kWh) 2015	θ_{yn} (gram/kWh) 2020
Coal	25	3724	0.3	5211	769	746
Gas	25	3222	0.32	2938	384.5	373
Hydro	40	4500	0.12	3424	0	0
Nuclear	50	11074	0.08	7861	0	0
Wind	30	9500	0.08	2047	0	0
Solar	25	15000	0.08	932	0	0
Biomass	25	10000	0.4	4356	0	0
LVE	2	433	0	2500	0	0
MVE	10	1439	0	4000	0	0
TVE	30	15152	0	4000	0	0
FCVE	10	5000	0	2500	0	0
AVE	10	3000	0	2000	0	0
SGVE	1	300	0	8760	0	0

(5) Energy Mix Constraints. According to the planning requirements, the proportion of nonfossil energy generation in the yth year has its lower limit

$$\sum_{n=ma}^{mb} P_{yn} \geq \alpha_y \cdot \sum_{n=1}^{mb} P_{yn} \quad (y = 1, 2, \ldots, Y), \tag{7}$$

where the first type to mbth type is conventional energy; the math type to mbth type is nonfossil energy; α_y represents the minimum proportion of nonfossil energy in total electricity generating in the yth year.

(6) CO_2 Emissions Constraints. Annual CO_2 emissions should not exceed the maximum allowable emissions

$$\sum_{n=1}^{N} P_{yn} \cdot 8760 \cdot \theta_{yn} \leq M_y \quad (y = 1, 2, \ldots, Y), \tag{8}$$

where M_y is the upper limit of CO_2 emissions in the yth year tonnes.

5. Case Study

According to the "12th Five-Year Plan" (TFP), the peak load, the total electricity consumption, and installed capacity are expected to reach 1040 gigawatts (GW), 6270 TWh, and 1437 GW, respectively, in 2015. Moreover, the peak load, the total electricity consumption, and installed capacity are expected to reach 1377 GW, 8200 TWh, and 1885 GW, respectively, in 2020 [20]. The power demand and installed capacity for each type of energy forecasting in 2015 and in 2020 are shown in Table 1.

IOCM is applied to the optimization of energy sources in 2015 and in 2020, respectively. In this model, 7 types of conventional energy sources, including coal, gas, hydro, nuclear, wind, solar, and biomass, and 6 types of virtual energy sources, including LVE, MVE, TVE, FCVE, AVE, and SGVE, are taken into consideration. The main parameters, presented in Table 2 come from the literatures [17–20] directly or are estimated based on literatures indirectly.

According to the results of IOCM, the total installed capacity will reach 1366 GW in 2015, of which the conventional energy is 1266 GW, while virtual energy is 100 GW. Moreover, the total installed capacity will reach 1837 GW in 2020, of which the conventional energy is 1630 GW, while virtual energy is 207 GW. Installed capacity for each type of conventional energy is shown in Table 3. It is obvious that lower-cost clean energy, such as hydro, wind, and nuclear power will have a rapid development. In comparison with TFP, in 2015, the installed capacity of coal-fired plants will decrease by 93 GW, accounting for 9.97% of the total installed capacity of coal-fired plants, while CO_2 emissions will decrease by 378 million tonnes (Mt), accounting for 10.02% of total emissions. Moreover, in 2020, installed capacity of coal-fired plants will decrease by 145GW, accounting for 12.50% of the total installed capacity of coal-fired plants, while CO_2 emissions will decrease by 573 million tonnes (Mt), accounting for 12.59% of the total emissions. The result of IOCM in comparison with TFP is shown in Table 4. As forecasted in Table 5, in 2015, CO_2 mitigation of virtual energy will reach 228 Mt, accounting for 60.39% of the total CO_2 mitigation. In 2020, CO_2 mitigation of virtual energy will reach 421 Mt, accounting for 73.43%.

Table 3: Installed capacity for each type of conventional energy in IOCM (GW).

	Coal	Gas	Hydro	Nuclear	Wind	Solar	Biomass	Total
2015	840	26	325	43	30	0.3	1.7	1266
2020	1015	30	390	90	100	2	3	1630

Table 4: The results of IOCM in comparison with TFP.

	2015			2020		
	Installed capacity of coal-fired plants (GW)	Electricity generation (TWh)	CO_2 emissions (Mt)	Installed capacity of coal-fired plants (GW)	Electricity generation (TWh)	CO_2 emissions (Mt)
TFP	933	6713	3773	1160	8770	4553
IOCM	840	5973	3395	1015	7636	3980
Reduction	93	740	378	145	1134	573

Table 5: CO_2 mitigation of virtual energy.

	2015		2020	
	Mitigation (Mt)	Proportion	Mitigation (Mt)	Proportion
LVE	77.15	20.41%	195.75	34.16%
MVE	6.40	1.69%	13.52	2.36%
TVE	83.94	22.21%	81.43	14.21%
FCVE	31.91	8.44%	81.13	14.16%
AVE	19.23	5.09%	36.70	6.41%
SGVE	9.63	2.55%	12.22	2.13%
Total	228.26	60.39%	420.75	73.43%

Consequently, promoting the development of smart grid constructions and DSM program, as well as adjusting the energy mix and improving energy efficiency are the most effective measures on CO_2 mitigation. The optimization of the CO_2 mitigation of power sector, under the premise of meeting the demand on electricity, leads to less CO_2 mitigation and installed capacity. Moreover, this could be a good solution to problems that are caused by factors like resources, capital, environmental, and other things and helps to achieve the goal of sustainable development.

6. Conclusions

Power sector is under tremendous pressure of CO_2 mitigation. Based on the discussion of all feasible measures, IOCM is proposed, which integrates the equivalent virtual energy, consisting of the energy saving capacity in both demand side and the power grid, with conventional energy in supply side. Then, the optimal plan of energy distribution, considering both economic benefits and mitigation benefits, can be figured out by multiobjective optimization calculations. The main conclusions are as follows.

(1) Development of measures on CO_2 mitigation should depend on the mature degree of technology. Large-sized replacement of small-sized coal-fired generation units with high efficient large-sized units is a mature technology deserving wide promotion. In the short and mediumterm, emphasis should be put on mature and low-cost generation technologies, such as hydropower, nuclear power, and wind power. Through more research funds, obstacles in the development of solar and CCS energy could be removed in the medium and long term.

(2) Since any single measure is far from the goal of CO_2 mitigation in power sector, emphasis should be put on the integrated application of various measures, including adjusting energy mix, improving energy efficiency in supply side, as well as the energy saving in demand side and power grid.

(3) Based on the data from TFP, IOCM is applied to the optimization of power energy resources in power sector in 2015 and in 2020. CO_2 mitigation is indirectly achieved by the development of DSM and smart grid constructions which lead to less demand and loss. The results indicate that development of DSM and the smart grid can make great contributions to CO_2 mitigation of power sector in China, reducing the CO_2 emissions by 10.02% and 12.59%, respectively, in 2015 and in 2020.

Acknowledgments

This study was supported by the Key Program of National Natural Science Foundation (nos. 50939001 and 41271543) and The Program for New Century Excellent Talents in University (NCET-09-0226).

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The Scientific World Journal
Volume 2012, Article ID 923183, 10 pages
doi:10.1100/2012/923183

The ScientificWorldJOURNAL

Research Article

Energy-Dominated Local Carbon Emissions in Beijing 2007: Inventory and Input-Output Analysis

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Received 8 September 2012; Accepted 23 September 2012

Academic Editors: B. Chen, T. Han-Song, and C. Zhan-Ming

For greenhouse gas (GHG) emissions by Beijing economy 2007, a concrete emission inventory covering carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) is presented and associated with an input-output analysis to reveal the local GHG embodiment in final demand and trade without regard to imported emissions. The total direct GHG emissions amount to $1.06E+08$ t CO_2-eq, of which energy-related CO_2 emissions comprise 90.49%, non-energy-related CO_2 emissions 6.35%, CH_4 emissions 2.33%, and N_2O emissions 0.83%, respectively. In terms of energy-related CO_2 emissions, the largest source is coal with a percentage of 53.08%, followed by coke with 10.75% and kerosene with 8.44%. Sector 26 (*Construction Industry*) holds the top local emissions embodied in final demand of $1.86E+07$ t CO_2-eq due to its considerable capital, followed by energy-intensive Sectors 27 (*Transport and Storage*) and 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*). The GHG emissions embodied in Beijing's exports are $4.90E+07$ t CO_2-eq, accounting for 46.01% of the total emissions embodied in final demand. The sound scientific database totally based on local emissions is an important basis to make effective environment and energy policies for local decision makers.

1. Introduction

The success of reducing GHG emissions depends greatly on the policies making at urban, domestic and international scales [1]. The international and domestic governments have established general policies (e.g., United Nations Climate Change Conference and China's 12th Five-Year Plan) [2, 3], but the policies enforced at the local level need to be improved by adding more detailed emission pictures within its own territory. Cities contribute 67% to the global GHG emissions from fossil energy use [4], so it is essential and urgent to implement reduction plans at the urban scale. As a result, this paper focuses on local energy inputs and GHG emissions in urban regions to guide environment and energy policies making at the substate level.

Many efforts have been made to calculate environmental emissions at the urban scale [1, 6–8], but most of them about urban carbon emissions just focus on the end-use emissions originated from industrial process, transportation, waste treatment, and so on [9–13], ignoring a deeper understanding of the total emissions in terms of both direct and indirect emissions caused by local commodities' production processes. In fact, all of the commodities consumed in cities lead to GHG emissions during their production processes [8]. For example, the water supply must base on the construction and operation of water works, from which intermediate inputs of steel, concrete, electricity, and so forth are consumed and indirect GHG emissions are produced. As a result, urban planning should consider GHG emissions embodied in commodities used as intermediate inputs to produce products or commodities consumed in cities, not just these obvious direct GHG emissions [5, 14].

To track both direct and indirect effects on embodiments for economies as socioecological systems, input-output analysis (IOA) [15–18] has been applied to analyze embodied GHG emissions [5, 8, 14], energy [19, 20], water resources [21–23], and so forth at urban, domestic, and international scales. Previous input-output studies usually discuss the total emissions (including local and imported emissions) under the assumption that imported commodities have the same embodied intensities as locally produced ones due to the lack of data, which blurs emission sources and responsibility allocation. However, this study highlights local emissions in view of local decision makers without regard to imported emissions. In doing this, based on local GHG emissions inventory, urban policymakers can make low-carbon plans to sustain the sustainable development of cities.

The rate of urbanization will increase from 40% in 2005 to 60% by 2030 in China along with the increasing living standard and the more energy-intensive lifestyle [6]. Taking Beijing as an example, its average annual economy growth rate exceeded 10% while energy consumption growth rate also overtook 6% over the period between 2000 and 2007 [24]. With the rapid development of economy and energy consumption in the near future, more emphasis should be laid on energy consumption and carbon emissions in Beijing.

With the latest available economic and environmental data, this paper calculates the local GHG emissions by 42 sectors of Beijing in 2007 and further analyzes the local emissions embodied in relevant economic activities based on systems IOA. The rest of this paper is organized as follows. In Section 2, methodological aspects of systems IOA based on the local ecological input-output table and data sources are described. Section 3 presents the direct GHG emissions inventory and corresponding embodiment analyses for Beijing 2007. Finally, we conclude this study in Section 4 by discussing the results and their implications.

2. Methodology and Data

2.1. Local Ecological Input-Output Table. In an attempt to model the local embodiment of natural resources consumption and environmental emissions, a local ecological input-output table extended from the economic input-output table with local economic flows (including local intermediate use and final demand) is compiled as Table 1, integrating direct GHG (including CO_2, CH_4, and N_2O) emissions flows within and across the boundary of the urban economy.

Taking Beijing as a case, to account the local economic flows, local intermediate use and final demand need to be obtained based on Beijing's competitive economy input-output table. Both intermediate use and final demand can be divided into three parts based on the proportion of local total output, domestic import, and foreign import [25–27]. Therefore, local intermediate input, z^L, can be calculated as

$$z_{ij}^{L} = z_{ij}\left(\frac{x_i}{\left(x_i + x_i^F + x_i^D\right)}\right), \qquad (1)$$

where z_{ij} is the total intermediate input from Sector i to Sector j, x_i is the total output of Sector i, x_i^F is the foreign imported economic flow of Sector i, and x_i^D is the domestic imported economic flow of Sector i. While final demand of Sector i from local output, f_i^L, is expressed as

$$f_i^{L} = f_i\left(\frac{x_i}{\left(x_i + x_i^F + x_i^D\right)}\right), \qquad (2)$$

where f_i is the total final demand of Sector i.

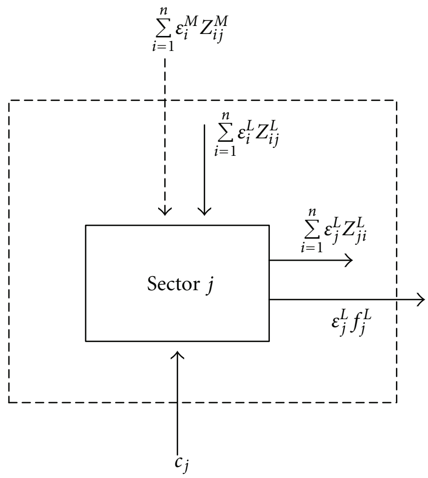

Figure 1: Embodied GHG flows for a typical sector in an urban economy (carbon flows introduced by imported commodities from other domestic and foreign regions $\sum_{i=1}^{n} \varepsilon_i^M z_{ij}^M$ are not considered based on local emissions).

2.2. Algorithm. From the perspective of local decision makers, this study focuses only on carbon flows coming from the urban system without taking into account carbon flows coming from the international and domestic systems. The embodied carbon flows for a typical sector in an urban economy based on local emissions can be described as Figure 1, including local and imported intra- and intersectoral carbon flows (ε_i^L is the local embodied intensity of products from Sector i, z_{ij}^L is the monetary value of local intermediate inputs from Sector i to Sector j, ε_i^M is the imported embodied intensity of products from Sector i, z_{ij}^M is the monetary value of imported intermediate inputs from Sector i to Sector j, ε_j^L is the local embodied intensity of products from Sector j, and z_{ji}^L is the monetary value of local intermediate inputs from Sector j to Sector i), carbon flows embodied in final demand (f_j^L denotes the final demand of Sector j from local outputs), and net environmental inputs flows (c_j is the amount of direct GHG emissions).

Based on Figure 1, the sectoral biophysical balance requires that

$$\varepsilon_j^L x_j = \sum_{i=1}^{n} \varepsilon_i^L z_{ij}^L + \sum_{i=1}^{n} \varepsilon_i^M z_{ij}^M + c_j, \qquad (3)$$

where x_j is the monetary value of total outputs of Sector j.

To calculate local embodied emissions in this paper, emissions introduced by imported commodities from other domestic and foreign regions are not concerned. Then, rewrite the physical balance equation as

$$\varepsilon_j^L x_j = \sum_{i=1}^{n} \varepsilon_i^L z_{ij}^L + c_j. \qquad (4)$$

Then an aggregate matrix equation can be induced as:

$$E^L X = E^L Z^L + C, \qquad (5)$$

Table 1: The local ecological input-output table (C is the direct GHG emissions matrix).

Input		Output										
		Intermediate use				Final demand						
		Sector 1	Sector 2	...	Sector n	Household consumption (rural)	Household consumption (urban)	Government consumption	Fixed capital formation	Inventory increase	Export to other domestic regions	Export to foreign regions
Local intermediate inputs	Sector 1											
	Sector 2		Z^L						F^L			
	...											
	Sector n											
Net environmental inputs	CO_2											
	CH_4		C									
	N_2O											

in which $E^L = [\varepsilon_j^L]_{1\times n}$, $Z^L = [z_{ij}^L]_{n\times n}$, $C = [c_j]_{1\times n}$, and $X = [x_{ij}]_{n\times n}$, where $i, j \in (1, 2, \ldots, n)$, $x_{ij} = x_j (i = j)$, and $x_{ij} = 0\ (i \neq j)$.

Therefore, with direct GHG emissions matrix C, local intermediate input matrix Z^L, and total outputs matrix X properly given, the embodied GHG emissions intensity matrix E^L can be calculated as

$$E^L = C\left(X - Z^L\right)^{-1}. \tag{6}$$

Though very similar to the conventional formula based on the widely assumed equal embodiment intensity for both the local and import products, the above formal equation for local embodiment intensity has different implications. It reflects the embodied intensity induced by local direct emissions but ignores that induced by imported emissions. Therefore, local direct and indirect emissions can be clearly demonstrated.

Evidently, the GHG emissions embodied in final demand activities, denoted by EEFD [5, 27], can be calculated as the product of embodied intensity and corresponding final demand volume from Sector j, as

$$\mathrm{EEFD}_j = \varepsilon_j^L f_j^L. \tag{7}$$

Emission embodied in trade is a useful indicator to reveal transferring carbon emissions. Focusing on local emissions, emissions embodied in trade include emissions embodied in exports but exclude emissions embodied in imports. Combining GHG emissions from other domestic and foreign regions, GHG emissions embodied in exports (EEE_j), including emissions embodied in exports to other domestic regions (EEE_j^D) and exports to foreign regions (EEE_j^F), can be expressed as

$$\mathrm{EEE}_j = \mathrm{EEE}_j^D + \mathrm{EEE}_j^F = \varepsilon_j^L e_j^D + \varepsilon_j^L e_j^F, \tag{8}$$

where e_j^D and e_j^F denote the export to other domestic regions and export to foreign regions of Sector j.

2.3. Data Sources. Most relevant environmental resources and economic data are adopted or derived from the recently issued official statistical yearbooks, such as Beijing Statistical Yearbook [28], China Agriculture Yearbook [29], China Energy Statistical Yearbook [30], China Environment Yearbook [31], China Industry Economics Statistical Yearbook [32], and China Statistical Yearbook for Regional Economy [33].

In this paper, all the three main GHG emissions of CO_2, CH_4, and N_2O are taken into consideration. The calculation of energy-related CO_2 emissions is based on a previous study [5], and the energy consumption data sources are from BSY and CESY by utilizing the default emission factors of IPCC [34]. For CO_2 emissions from industrial processes, the data of industrial products can be found in BSY, CIESY, and other sources. And corresponding emission factors are also adopted from IPCC combined with Chen and Zhang [14]. As to CH_4 and N_2O, the data from different emission sources are derived from BSY, CAY, CESY, CEY, CIESY, and other

Table 2: Sectors for Beijing's economic input-output table 2007 [5].

Code	Sector
1	Farming, Forestry, Animal Husbandry, Fishery, and Water Conservancy (Agriculture)
2	Coal Mining and Dressing
3	Petroleum and Natural Gas Extraction
4	Ferrous and Nonferrous Metals Mining and Dressing
5	Nonmetal and Other Minerals Mining and Dressing
6	Food Processing, Food Production, Beverage Production, and Tobacco Processing
7	Textile Industry
8	Garments and Other Fiber Products, Leather, Furs, and Down and Related Products
9	Timber Processing, Bamboo, Cane, Palm and Straw Products, and Furniture Manufacturing
10	Papermaking and Paper Products, Printing and Record Medium Reproduction, and Cultural, Educational, and Sports Articles
11	Petroleum Processing and Coking, Gas Production and Supply
12	Raw Chemical Materials and Chemical Products, Medical and Pharmaceutical Products, Chemical Fiber, Rubber Products, and Plastic Products (Chemical Products Related Industry)
13	Nonmetal Mineral Products
14	Smelting and Pressing of Ferrous and Nonferrous Metals
15	Metal Products
16	Ordinary Machinery, Equipment for Special Purpose
17	Transportation Equipment
18	Electric Equipment and Machinery
19	Electronic and Telecommunications Equipment
20	Instruments, Meters Cultural and Office Machinery
21	Manufacture of Artwork and Other Manufactures
22	Waste
23	Electric Power/Steam and Hot Water Production and Supply
24	Gas Production and Supply Industry
25	Water Production and Supply Industry
26	Construction Industry
27	Transport and Storage
28	Post
29	Information Transmission, Computer Services and Software
30	Wholesale, Retail Trade
31	Hotels, Catering Service
32	Financial Industry
33	Real Estate
34	Leasing and Commercial Services
35	Research and Experimental Development
36	Polytechnic Services
37	Water conservancy, Environment and Public Facilities Management

Table 2: Continued.

Code	Sector
38	Service to Households and Other Service
39	Education
40	Health, Social Security, and Social Welfare
41	Culture, Sports, and Entertainment
42	Public Management and Social Organization

Table 3: Anthropogenic methane emissions by source.

Item	CH_4 emission (t)	Fraction
(1) Agriculture activities	$2.50E+00$	21.21%
Enteric fermentation	$2.10E+00$	17.79%
Manure management	$3.01E-01$	2.55%
Field burning of agricultural residues	$1.02E-01$	0.86%
(2) Fugitive emissions	$2.77E+00$	23.46%
Coal mining	$1.63E+00$	13.81%
Oil and natural gas systems	$1.14E+00$	9.66%
(3) Fossil fuel combustion	$1.69E-01$	1.43%
(4) Waste	$6.36E+00$	53.90%
Municipal solid waste	$5.37E+00$	45.48%
Industrial waste water	$4.90E-01$	4.15%
Domestic sewage	$5.03E-01$	4.26%
(5) Total	$1.18E+01$	100.00%

databases. Since some specific emission factors need to suit the Chinese situation, this paper adopts the emission factors from Chen and Zhang [14].

Obtained from the most recently available Beijing Bureau of Statistics, the Beijing's economic input-output table 2007 is adopted. In this table, the Beijing economy is divided into 42 sectors, including 1 sector for the first industry, 25 sectors for the second industry, and 16 sectors for the third industry, as listed in Table 2. The economic flows of input-output table are based on producer prices in 2007 with a unit of ten thousand Chinese Yuan.

3. Results

3.1. Direct Emissions

3.1.1. Carbon Dioxide. The total direct CO_2 emissions amount to $1.01E+08$ t. Guo et al. [5] provide a detailed inventory of energy-related direct CO_2 emissions by fuel consumption in Beijing. As the largest emission source, fuel combustion contributes to 93.44% of total. Among the emissions from fuel combustion, the largest source is coal with a percentage of 53.08%, followed by coke with 10.75% and kerosene with 8.44% (see Figure 2).

Compared with fuel consumption, industrial processes are only responsible for $6.64E+06$ t CO_2 emissions (6.56%), of which $4.44E+02$ t is contributed by manufacturing of cement (4.39%), $1.24E+02$ t is by smelting and pressing of steel (1.22%), $9.37E+01$ t is by smelting and pressing of pig iron (0.93%) and $2.35E+00$ t is by manufacturing of glass (0.02%).

Table 4: Anthropogenic nitrous oxide emissions by source.

Item	N_2O emission (t)	Fraction
(1) Fossil fuel combustion	$1.19E-01$	41.91%
(2) Agriculture activities	$1.65E-01$	58.09%
Manure management	$8.01E-02$	28.20%
Cropland	$8.31E-02$	29.23%
Field burning of agricultural residues	$1.90E-03$	0.67%
(3) Total	$2.84E-01$	100.00%

3.1.2. Methane. The main sources of CH_4 emission include agricultural activities (enteric fermentation, manure management, and field burning of plant residues), fugitive emissions (coal mining, oil and natural gas leakage), fossil fuel consumption, and waste (municipal solid waste, industrial wastewater, and domestic sewage) [14]. From the calculation, it is obtained that the total CH_4 emissions amount to $1.18E+01$ t. As the most important source of methane emissions, the solid waste accounts for 45.48% of total, followed by enteric fermentation and coal mining with 17.79% and 13.81%, respectively. However, fossil fuel consumption only accounts for 1.43% of total, as shown in Table 3.

As the main source, agriculture activities cause $2.50E+00$ t CH_4, of which emissions from enteric fermentation amount to $2.10E+00$ t as 17.79% of total, followed by manure management and field burning of agricultural residues with the fractions of 2.55% and 0.86%.

Fugitive CH_4 emission sources in Beijing include coal mining with oil and natural gas systems, of which the CH_4 emissions are $1.63E+00$ t and $1.14E+00$ t, respectively. The total fugitive CH_4 emissions are $2.77E+00$ t, accounting for 23.46% of total.

With expansion of urban population, urban waste problems become increasingly severe. Among the CH_4 emissions of waste, emissions from municipal solid waste ($5.37E+00$ t, 45.48% of total) play a main role compared to industrial waste water ($4.90E-01$ t, 4.15% of total) and domestic sewage ($5.03E-01$ t, 4.26% of total).

3.1.3. Nitrous Oxide. Direct N_2O emissions in Beijing from main sources like agricultural activities (manure management, cropland, and field burning of agricultural residues) and fuel combustion (see Table 4) are estimated in this paper. The total emissions of N_2O from all sources amount to $2.84E-01$ t, which are far less than those of CO_2 and CH_4 by mass, but the global warming potential of N_2O is the greatest among these three greenhouse gases ($CO_2 : CH_4 : N_2O = 1:21:310$).

Considerable N_2O emissions are caused by agricultural activities (58.09%) in Beijing. Cropland contributes the most to N_2O emissions from annual synthetic fertilizer (29.23%), followed by manure management (28.20%) and field burning of agricultural residues (0.67%). Besides, the

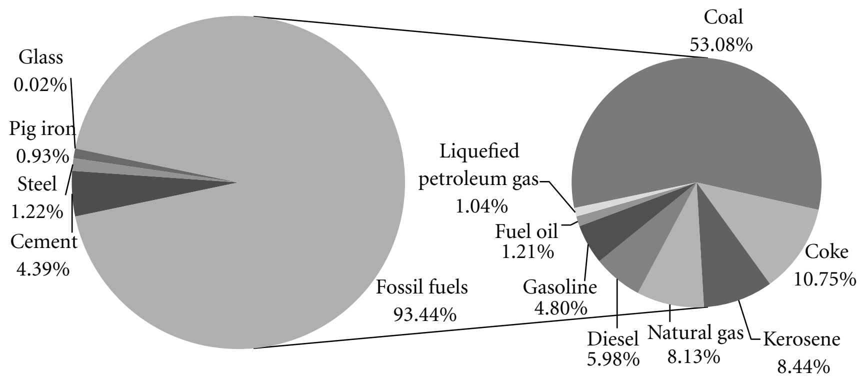

Figure 2: The components of direct CO_2 emissions by source.

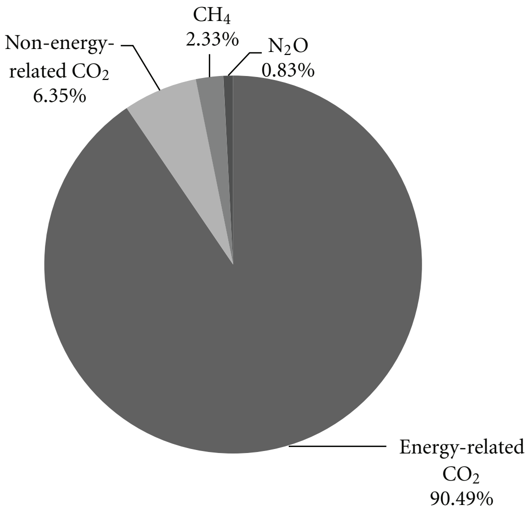

Figure 3: The components of GHG emissions.

N_2O emissions from fuel combustion are $1.19E-01$ t, 41.91% of total in Beijing. Since Beijing has no nitric acid and adipic acid products, N_2O emission coming from industrial processes can be ignored.

As to N_2O emissions by sector, agriculture sector contributes to the largest emissions ($1.67E-01$ t, 58.77% of total), which is due to massive N_2O emissions from cropland and manure management, while other sectors perform poorly in N_2O emissions. Therefore, effective management and control of agriculture activities is an effective way to reduce N_2O emissions.

3.1.4. Total Emissions. The total direct GHG emissions amount to $1.06E+08$ t CO_2-eq in Beijing 2007 by the commonly referred IPCC global warming potentials, of which energy-related CO_2 contributes to $9.45E+07$ t CO_2-eq (90.49% of total), non-energy-related CO_2 $6.64E+06$ t CO_2-eq (6.35% of total), CH_4 $2.48E+06$ t CO_2-eq (2.33% of total), and N_2O $8.81E+05$ t CO_2-eq (0.83% of total) as shown in Figure 3.

With all the categories mentioned above, total direct GHG emissions are presented in Table 5, of which Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) contributes to the largest share of GHG emissions, which amount to $2.79E+07$ t CO_2-eq (26.20% of total), followed by Sectors 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*), 27 *(Transport and Storage),* and 13 *(Nonmetal Mineral Products)* with $2.08E+07$ t CO_2-eq (19.54% of total), $1.43E+07$ t CO_2-eq (13.40% of total), and $1.03E+07$ t CO_2-eq (9.68% of total), respectively. Sector 23 is the energy conversion sector, while Sectors 14, 27, and 13 are all energy-intensive sectors. A host of GHG emissions are derived from aluminum production in Sector 14, and Sector 13 emits considerable GHG due to the production of nonmetallic mineral products including concrete and glass besides energy-related emissions.

With comparison of GHG emissions shown in Table 5, it is noted that CH_4 and N_2O emissions are tiny, excluding those in Sectors 1 *(Agriculture)* and 2 *(Coal Mining and Dressing)* attributed to agricultural activities and fugitive emissions. Direct CH_4 emissions of Sectors 1 and 2 amount to $5.26E+05$ and $3.42E+05$ t CO_2-eq, accounting for 21.22% and 13.80% of the total CH_4 emissions. Sector 1 is the leading N_2O emission sector with $5.18E+05$ t CO_2-eq, accounting for 81.27% of the total N_2O emissions.

3.2. Embodied Emissions

3.2.1. Embodied Emission Intensity. As presented in Figure 4 for the local embodied GHG emission intensities of 42 sectors in Beijing 2007 based on (6) and Table 5, Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) has the largest intensity of 7.06 t CO_2-eq/$1E+4$ Yuan, followed by Sectors 5 (*Nonmetal and Other Minerals Mining and Dressing*), 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*), and 13 (*Nonmetal Mineral Products*) with intensities of 6.67, 4.93, and 4.55 t CO_2-eq/$1E+4$ Yuan, respectively. More evidently, these high-intensity sectors are all characterized by remarkable direct emissions.

According to the emission type, embodied GHG emission intensities of most industries are dominated by the embodied CO_2 emission industries, except for Sectors 2

Table 5: Direct GHG emissions by type and sector.

Sector code	CO_2 (t)	CH_4 (t CO_2-eq)	N_2O (t CO_2-eq)	Total GHGs (t CO_2-eq)	Fraction
1	3.44E + 06	5.26E + 05	5.18E + 05	4.48E + 06	4.21%
2	5.96E + 04	3.42E + 05	2.70E + 02	4.02E + 05	0.38%
3	3.81E + 04	2.39E + 05	9.58E + 01	2.78E + 05	0.26%
4	9.81E + 04	4.19E + 01	4.06E + 02	9.86E + 04	0.09%
5	2.16E + 05	8.11E + 01	8.71E + 02	2.17E + 05	0.20%
6	1.58E + 06	4.69E + 04	7.27E + 03	1.64E + 06	1.54%
7	2.39E + 05	1.94E + 04	1.10E + 03	2.60E + 05	0.24%
8	3.24E + 05	9.54E + 01	1.48E + 03	3.25E + 05	0.31%
9	9.17E + 04	3.90E + 01	3.53E + 02	9.21E + 04	0.09%
10	4.66E + 05	2.97E + 04	1.92E + 03	4.97E + 05	0.47%
11	1.19E + 06	4.89E + 02	2.71E + 03	1.19E + 06	1.12%
12	2.99E + 06	1.01E + 04	1.33E + 04	3.02E + 06	2.83%
13	1.03E + 07	1.68E + 03	2.63E + 04	1.03E + 07	9.68%
14	2.07E + 07	3.96E + 03	8.43E + 04	2.08E + 07	19.54%
15	2.27E + 05	9.59E + 01	8.55E + 02	2.28E + 05	0.21%
16	8.19E + 05	2.63E + 02	3.50E + 03	8.23E + 05	0.77%
17	9.11E + 05	2.88E + 02	3.78E + 03	9.15E + 05	0.86%
18	1.22E + 05	5.17E + 01	4.17E + 02	1.23E + 05	0.12%
19	1.32E + 05	6.12E + 01	1.99E + 02	1.32E + 05	0.12%
20	3.73E + 04	2.02E + 01	1.19E + 02	3.74E + 04	0.04%
21	2.09E + 05	5.54E + 01	9.75E + 02	2.10E + 05	0.20%
22	8.67E + 03	4.47E + 00	3.31E + 01	8.71E + 03	0.01%
23	2.78E + 07	6.74E + 03	1.28E + 05	2.79E + 07	26.20%
24	1.18E + 05	6.06E + 01	1.34E + 02	1.18E + 05	0.11%
25	1.70E + 04	8.34E + 00	4.84E + 01	1.71E + 04	0.02%
26	1.27E + 06	3.04E + 05	3.78E + 03	1.57E + 06	1.48%
27	1.42E + 07	8.00E + 04	3.58E + 04	1.43E + 07	13.40%
28	7.74E + 05	6.91E + 04	1.96E + 03	8.45E + 05	0.79%
29	1.83E + 05	6.85E + 04	4.70E + 02	2.52E + 05	0.24%
30	1.81E + 06	1.07E + 05	5.04E + 03	1.93E + 06	1.81%
31	2.73E + 06	1.06E + 05	5.20E + 03	2.84E + 06	2.67%
32	1.47E + 05	4.68E + 04	4.24E + 02	1.94E + 05	0.18%
33	3.54E + 06	4.78E + 04	1.18E + 04	3.60E + 06	3.38%
34	1.20E + 06	4.73E + 04	4.02E + 03	1.25E + 06	1.17%
35	4.15E + 05	4.69E + 04	1.33E + 03	4.63E + 05	0.43%
36	4.15E + 05	4.69E + 04	1.33E + 03	4.63E + 05	0.43%
37	4.26E + 05	4.69E + 04	1.48E + 03	4.74E + 05	0.45%
38	8.28E + 05	4.70E + 04	2.89E + 03	8.78E + 05	0.82%
39	1.63E + 06	4.73E + 04	4.85E + 03	1.69E + 06	1.58%
40	5.05E + 05	4.69E + 04	1.47E + 03	5.53E + 05	0.52%
41	2.83E + 05	4.69E + 04	7.52E + 02	3.30E + 05	0.31%
42	7.19E + 05	4.71E + 04	2.32E + 03	7.68E + 05	0.72%
Total	1.03E + 08	2.48E + 06	8.81E + 05	1.06E + 08	100.00%

(*Coal Mining and Dressing*) and 3 (*Petroleum and Natural Gas Extraction*). The shares of CH_4 emission intensities of Sectors 1 (*Agriculture*), 2 (*Coal Mining and Dressing*), and 3 (*Petroleum and Natural Gas Extraction*) are especially high. The proportion of N_2O emissions intensities for most sectors is small except for Sector 1 (*Agriculture*) since agriculture activities are the main sources of N_2O emissions.

3.2.2. Emissions Embodied in Final Demand. As shown in Figure 5, the final demand activities of Beijing in terms of embodied GHG emissions are presented according to (7). The largest GHG-emission sector is Sector 26 (*Construction Industry*) with 1.86E + 07 t CO_2-eq due to its considerable fixed capital. With the strong growth of construction in Beijing, lots of direct and indirect inputs (e.g., cement,

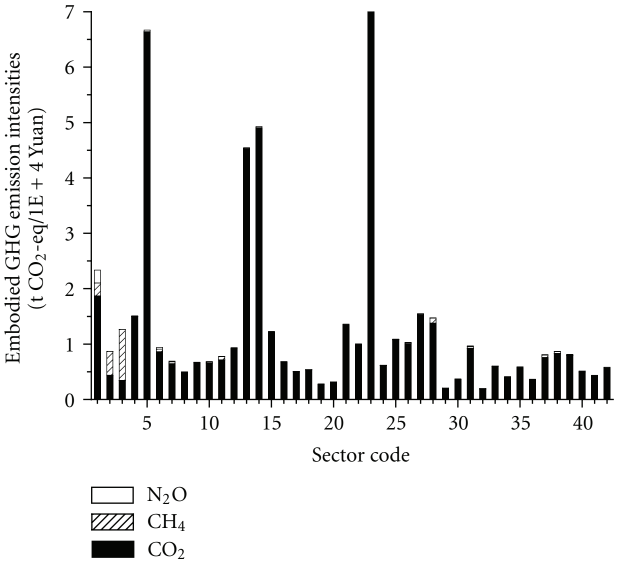

FIGURE 4: Embodied GHG emission intensities of 42 sectors.

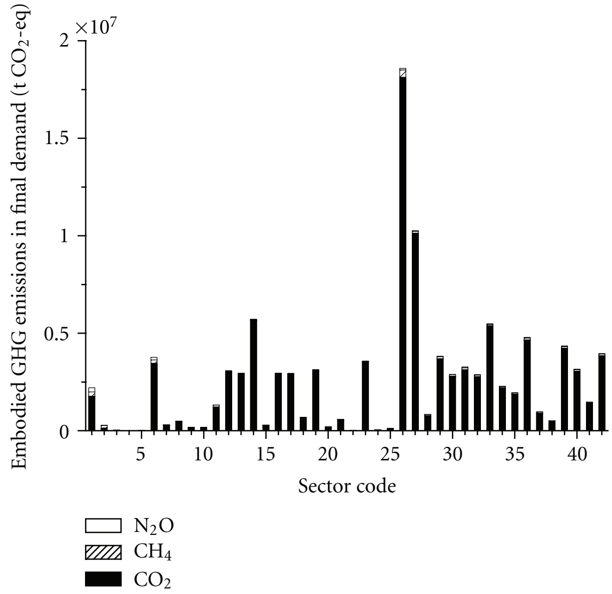

FIGURE 5: Emissions embodied in final demand.

metal, and energy) are produced during these construction activities, which lead to a great deal of carbon emissions. Sectors 27 (*Transport and Storage*) and 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*) provide the second and third largest emissions of $1.03E + 07$ and $5.72E + 06$ t CO_2-eq, mainly attributed to their substantial exports to foreign regions and other domestic regions, respectively. Besides, GHG emissions of Sector 27 are also introduced by massive government consumption and urban household consumption with rising traffic consumption level. Most sectors have prominent peaks on CO_2 emissions; Sectors 1 (*Agriculture*) and 6 (*Food Processing, Food Production, Beverage Production,* and *Tobacco Processing*) are also with massive CH_4 emissions due to agriculture activities, while Sector 26 (*Construction Industry*) are due to high energy usage. Especially for Sector 2 (*Coal Mining and Dressing*), CH_4 emissions contribute to 49.37% of the total due to this particular industrial process in Beijing.

Regarding the seven final demand categories (see Figure 6), emissions embodied in exports to other domestic regions have the largest value of $3.52E+07$ t CO_2-eq, accounting for 33.10% of total. Besides, GHG emissions embodied in fixed capital formation are responsible for 23.83% of total due to intensive investment with the urban construction boom in Beijing. Emissions embodied in rural household consumption ($1.55E + 06$ t CO_2-eq, 1.46% of total) are just 9.86% of those in urban household consumption ($1.57E + 07$ t CO_2-eq, 14.78% of total). Emissions embodied in government consumption ($1.19E + 07$ t CO_2-eq, 11.22% of total) are 30.89% less than those in household consumption (urban and rural).

3.2.3. Emissions Embodied in Exports. Since local emissions embodied in trade only focus on emissions induced by local direct emissions but do not take imports into account, this paper just studies the exports to foreign regions and other domestic regions excluding imports. The distribution of embodied emissions from the exports in 42 sectors is presented in Figure 7. The GHG emission embodied in Beijing's exports is $4.90E + 07$ t CO_2-eq, accounting for 46.01% of the total emissions in final use. The total EEE^D ($3.52E+07$ t CO_2-eq) are 2.56 times larger than the total EEE^F ($1.37E + 07$ t CO_2-eq) for Beijing. The largest exporting sector is Sector 27 (*Transport and Storage,* $9.37E+06$ t CO_2-eq, 19.12% of total), followed by Sectors 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals,* $4.72E + 06$ t CO_2-eq, 9.64% of total), 36 (*Polytechnic Service,* $3.90E+06$ t CO_2-eq, 7.96% of total), and 19 (*Electronic and Telecommunications Equipment,* $1.85E + 06$ t CO_2-eq, 5.82% of total). As a whole, most sectors have the larger EEE^D except for some large foreign trade export sectors, for example, Sectors 1, 3, 7, 8, 19, 30, 34, and 42 with larger EEE^F.

4. Concluding Remarks

This paper provides a systematic and detailed calculation on the embodiment of local GHG emissions at urban scale through the extended economic input-output analysis with the case study of Beijing 2007. As a result, a local direct GHG emissions inventory and corresponding embodiment analyses are assessed.

The total direct GHG emissions amount to $1.06E + 08$ t CO_2-eq in Beijing. For the total emissions structure, energy-related CO_2 emissions comprise 90.49%, non-energy-related CO_2 emissions 6.35%, CH_4 emissions 2.33%, and N_2O emissions 0.83%. Among the emissions from fuel combustion, the largest source is coal with a percentage of 53.08%, followed by coke with 10.75% and kerosene with 8.44%. Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) is the largest direct emissions sector for the Beijing economy in 2007, followed by energy-intensive

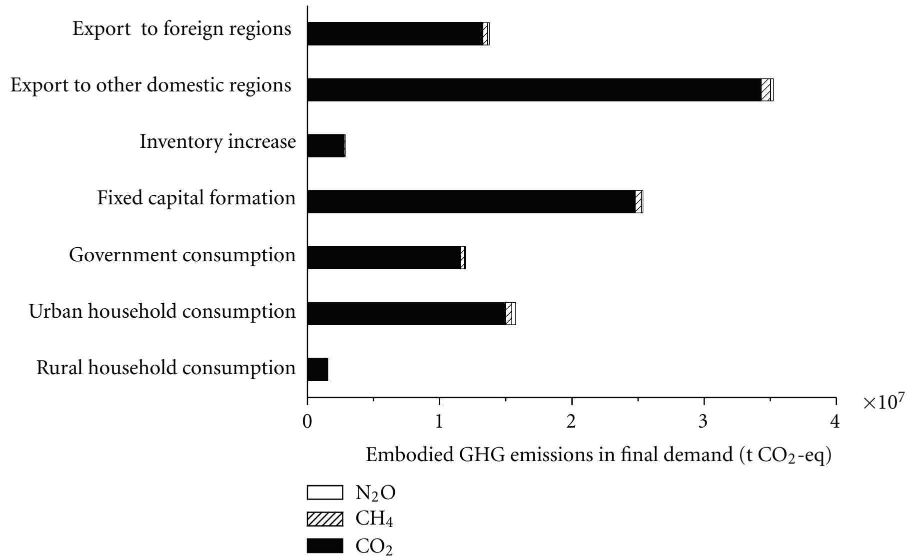

FIGURE 6: The components of embodied GHG emissions by final demand category.

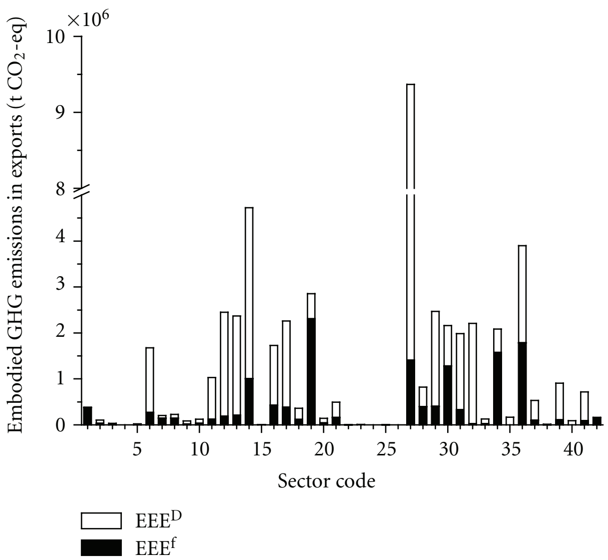

FIGURE 7: Emissions embodied in exports.

Sectors 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*), 27 *(Transport and Storage),* and 13 *(Nonmetal Mineral Products)*.

For the final demand of Beijing in terms of embodied CO_2 emissions, Sector 26 (*Construction Industry*) provides the largest emissions of $1.86E + 07$ t CO_2-eq due to its considerable capital during the concerned year. Sectors 27 (*Transport and Storage*) and 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*) provide the second and third largest emissions of $1.03E + 07$ and $5.72E + 06$ t CO_2-eq.

The GHG emissions embodied in Beijing's exports are $4.90E + 07$ t CO_2-eq, accounting for 46.01% of the total emissions in final demand. The total EEE^D ($3.52E+07$ t CO_2-eq) are 2.56 times larger than the total EEE^F ($1.37E + 07$ t CO_2-eq) for Beijing. The largest exporting sector is Sector 27 (*Transport and Storage)*, followed by Sectors 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*), 36 (*Polytechnic Service*), and 19 (*Electronic and Telecommunications Equipment*).

Resulted embodied local GHG intensities for sectors indicate the average amount of local emissions embedded in one economic unit of local product, which provide sound scientific data for local policy makers to adjust industrial structure and energy consumption structure in order to relieve global climate change. From the perspective of local decision makers, this study is an important basis when local environment and energy policies are making.

Expansion of industrial scale has been the main driving factor of energy consumption and carbon emissions. While the change of industrial structure and maximize energy efficiency are effective measures to conserve energy and reduce emissions. Specific measures are as follows: (1) In terms of energy efficiency, local government continuously eliminates high-energy-consumption industries and backward production capacity. In the meantime, they should in favor of high and advanced production technology to maximize energy efficiency, especially for some high-energy-consumption or high-resource-consumption industries, such as Sectors 23 (*Electric Power/Steam and Hot Water Production and Supply*), 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*), etc. (2) Industrial structural change makes great impact on carbon emissions structure. Beijing has made great efforts for industrial structural change, for example, Beijing is greatly developing the tertiary industries and reducing the proportion of primary industries and secondary industries. However, detailed industrial structure should be adjusted based on the carbon consuming responsibilities.

Acknowledgments

This study has been supported by Innovation Project Foundation of Beijing Academy of Science and Technology (Grant no. PXM2011_178215_000003).

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The Scientific World Journal
Volume 2012, Article ID 515468, 6 pages
doi:10.1100/2012/515468

Research Article

Double-Grating Displacement Structure for Improving the Light Extraction Efficiency of LEDs

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Received 1 September 2012; Accepted 18 September 2012

Academic Editors: B. Chen, T. Han-Song, and C. Zhan-Ming

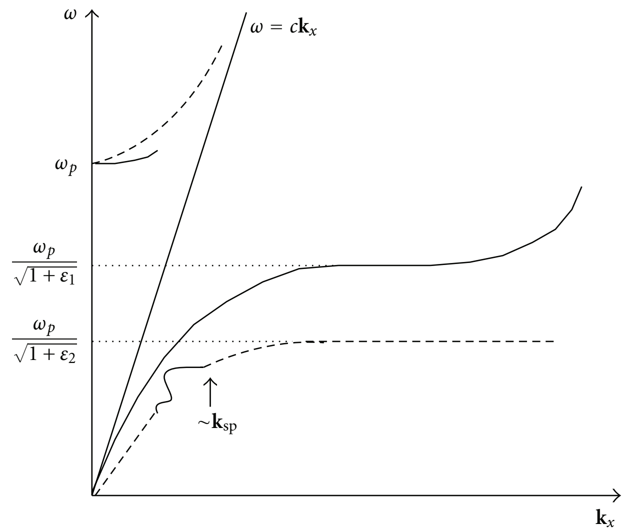
To improve the light extraction efficiency of light-emitting diodes (LEDs), grating patterns were etched on GaN and silver film surfaces. The grating-patterned surface etching enabled the establishment of an LED model with a double-grating displacement structure that is based on the surface plasmon resonance principle. A numerical simulation was conducted using the finite difference time domain method. The influence of different grating periods for GaN surface and silver film thickness on light extraction efficiency was analyzed. The light extraction efficiency of LEDs was highest when the grating period satisfied grating coupling conditions. The wavelength of the highest value was also close to the light wavelength of the medium. The plasmon resonance frequencies on both sides of the silver film were affected by silver film thickness. With increasing film thickness, plasmon resonance frequency tended toward the same value and light extraction efficiency reached its maximum. When the grating period for the GaN surface was 365 nm and the silver film thickness was 390 nm, light extraction efficiency reached a maximum of 55%.

1. Introduction

Low-carbon economy and green economy have recently become major themes of global development. As a type of green lighting energy, light-emitting diodes (LEDs) have attracted considerable research attention [1]. LEDs present the advantages of energy conservation, environment friendliness, fast response, and long lifetimes. Thus, LEDs lighting systems have been considered to reduce greenhouse gas emissions by replacing fuel-based lighting in the developing world [2]. Not only that, these light sources are extensively used as backlight sources of liquid crystal displays, advertisements, night lights, traffic signals, outdoor lighting, full color displays [3], and biometric devices [4], in addition, the array of LEDs has been used to inactivate bacteria in liquid suspension and on exposed surfaces [5], among other applications. Despite these advantages, the development of LED core technology is constrained by the photons produced in the lighting devices. Such a constraint prevents photons from being effectively radiated and converted into available optical power. This problem stems from the inherent structure of solid-state lighting devices: the refractive index of solid semiconductor luminophore is higher than that of the surrounding medium [6]. Thus, the light emitted by the lighting devices easily causes total internal reflection in the interface of semiconductor and air, after which the light retraces the optical path of the luminophore and is converted into heat [7]. This phenomenon makes the LEDs working in high-temperature environments for a long time; it not only wastes energy, but also shortens LED lifetimes. So the improvement of LEDs light extraction efficiency can not only extend lifetime, but also make important contribution to the development of the new green energy.

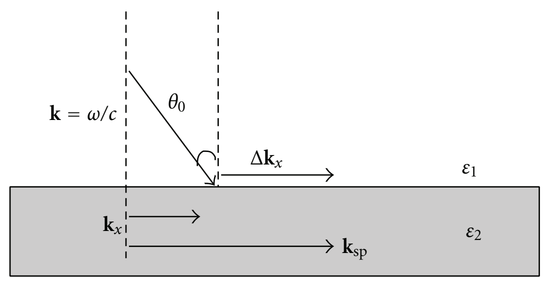
Foreign and domestic experts have begun improving the structure of LED chips, thereby significantly enhancing light extraction efficiency. These improvements primarily include changing the geometric shape of the chips, reducing the duration of total internal reflection in the chips, and decreasing light energy losses. The methods generally applied in realizing such enhancements are using the inverted pyramid structure [8, 9], performing surface roughening [10], constructing a mirror with Bragg grating reflection [11], and creating a two-dimensional photonic crystal structure on the surface of GaN [12–15]. Using the characteristic of surface plasmons (SPs) to enhance the light extraction efficiency of LEDs has recently become a research focus [16]. Compare with a single grating structure of the LED model described in [17]. In the current work, a double-grating displacement structure was constructed for an LED model to improve the light extraction efficiency of LEDs. The structure was realized by etching grating patterns on GaN and metallic silver film surfaces.

Under certain conditions, the free electrons of metal surfaces produce collective coherent oscillation, which is stimulated by light; the electromagnetic wave at the metal/air interface is called SP [18, 19]. The internal quantum efficiency and external quantum efficiency of LEDs can be improved by using SPs. The improvement in the internal quantum efficiency of LEDs by applying SPs is based on a principle that is related to the spontaneous radiative rate of excitons and state density [20]. When the light center is located in the micro cavity of the wavelength scale, the state density of photons changes, which, in turn, causes variations in the spontaneous radiation rate of excitons. The principle governing the use of SPs to improve the external quantum efficiency of LEDs is based on the observation that light can excite SPs. The light reflection angle is greater than the total internal reflection angle, but the former prevents light from radiating outward. A reasonable metal structure can excite SPs, which are then radiated outward in the form of light. Part of the SPs can be coupled to the electromagnetic waves on the surface of metal, and radiated outward in the form of light by etching a grating-coupled structure on the surface. Part of the incident light that causes total internal reflection can be diminished by grating-patterned etching of the GaN surface. Reducing total internal reflection can also be realized by using a dielectric material with a high coefficient. Using this material produces an evanescent field in total internal reflection. The evanescent field is used as the excitation source that stimulates the SP resonance. It can effectively extract a limited amount of light and reduce the junction temperature of LED chips. Compared with the traditional LED structure, the grating etched onto the GaN surface is relatively complex when used without system optimization. In this work, therefore, the grating period for GaN and metallic silver film thickness was optimized. The influence of these parameters on light extraction efficiency was also simulated and analyzed.



ω: Incident light frequency.
c: Light velocity.
$\varepsilon_1\varepsilon_2$: Material dielectric constant.

Figure 1: Dispersion relationship curve of SPs.



$\mathbf{k}$: Incident light vector
θ_0: Considered angle of incident light and normal line

Figure 2: SPs excited by light.

2. Theories and Methods

2.1. Introduction to SP Resonance. When the wave frequency for the excitation of SPs is larger than the plasmon resonance frequency (ω_p), the electromagnetic field is radiatively propagated far from the space between the metal/dielectric material interface, a phenomenon described as the radiative mode of SPs [20, 21]. Only when the horizontal direction wave vector $\mathbf{k}_x$ is very small (i.e., resonance frequency $\approx \omega_p$) can the life cycle of the radiant mode of SPs on a metal surface be defined. The gradual increase in $\mathbf{k}_x$ results in a resonance mode life cycle that is too short to have any practical significance. The SP resonance in the range of visible frequency is the nonradiative SP mode. The electromagnetic field produced by this mode is limited to an area near the metal surface. This phenomenon is called electromagnetic wave dispersion.

The SP dispersion relationship is depicted in Figure 1. The dispersion curve of the nonradiative SPs produced on a metal surface lies completely on the right side of the incident electromagnetic wave line of the dielectric material [20]. This result indicates that the SPs have a longer horizontal component of wave vector $\mathbf{k}_{sp}$ than that of the incident electromagnetic wave vector $\mathbf{k}_x$ of the same energy. Thus, the general electromagnetic waves incident from the dielectric material cannot stimulate nonradiative SPs and reach the resonance mode. To match the excitation conditions for the SP resonance mode, a coupled mechanism should be applied. This mechanism increases wave vector $\Delta\mathbf{k}_x$ and causes the incident electromagnetic wave to achieve a higher $\mathbf{k}_x$ (Figure 2).

Two coupled mechanisms are commonly used [20]. One involves producing a small-raster periodic structure on a metal surface as a coupled medium. Under an external electromagnetic field, the free electrons of the metal surface in these cycle structures cause polarized electron oscillation for a specific wavelength. The generated electromagnetic field can provide an additional value $\Delta\mathbf{k}_x$ to the incident electromagnetic wave. Subsequently, SP resonance is stimulated. The other coupled mechanism uses the total internal reflection dissipation field produced in a material with a high dielectric constant as the excitation source to stimulate SP resonance.

The electromagnetic wave vector can be written as

$$\mathbf{k}^2 = \frac{\omega^2 \varepsilon\mu}{c^2}, \tag{1}$$

where ε and μ are the relative permittivity and relative permeability of the material, respectively. When the electromagnetic wave passes through the prism of high permittivity, the wave vector is greater than that observed in dielectric material ε_1. When the incident light produces total internal reflection in the prism/dielectric material interface, part of the evanescent field is tunneled into the dielectric material near the total internal reflection interface. The wave vector $\mathbf{k}_x$ of the evanescent field and the total internal reflection wave vector have the same size when the distance between the prism and the metal surface is sufficiently small. At the same time, when the incident light wave vector horizontal component of total internal reflection satisfies the conditions of SPs, the SPs in the dielectric material/metal interface are stimulated.

2.2. Finite Difference Time Domain Method. The finite difference time domain (FDTD) method [22], an extension of the finite difference method, is a numerical analysis approach that directly performs computer simulations by using Maxwell equations for electromagnetic fields. Using the Maxwell curl equations in accordance with the field quantities that have special configurations in the Yee grid yields [23, 24]

$$\begin{aligned}
&\frac{\varepsilon(i+1/2,j,k)\left[\mathbf{E}_x^{n+1}(i+1/2,j,k) - \mathbf{E}_x^{n}(i+1/2,j,k)\right]}{\Delta t} \\
&\quad + \frac{\sigma(i+1/2,j,k)\left[\mathbf{E}_x^{n+1}(i+1/2,j,k) + \mathbf{E}_x^{n}(i+1/2,j,k)\right]}{2} \\
&\quad = \frac{\left[\mathbf{H}_z^{n+1/2}(i+1/2,j+1/2,k) - \mathbf{H}_z^{n+1/2}(i+1/2,j-1/2,k)\right]}{\Delta y} \\
&\quad - \frac{\left[\mathbf{H}_y^{n+1/2}(i+1/2,j,k+1/2) - \mathbf{H}_y^{n+1/2}(i+1/2,j,k-1/2)\right]}{\Delta z}.
\end{aligned} \tag{2}$$

Let

$$\begin{aligned}
p &= \left(i+\frac{1}{2}, j, k\right), \qquad q^+ = \left(i+\frac{1}{2}, j+\frac{1}{2}, k\right), \\
q^- &= \left(i+\frac{1}{2}, j-\frac{1}{2}, k\right), \\
r^+ &= \left(i+\frac{1}{2}, j, k+\frac{1}{2}\right), \qquad r^- = \left(i+\frac{1}{2}, j, k-\frac{1}{2}\right).
\end{aligned} \tag{3}$$

Thus,

$$\begin{aligned}
(\mathbf{E}_x)_p^{n+1} &= \frac{\left[1 - \Delta t\sigma_p/2\varepsilon_p\right](\mathbf{E}_x)_p^n}{\left[1 + \Delta t\sigma_p/2\varepsilon_p\right]} \\
&\quad + \frac{\left(\Delta t/\varepsilon_p\right)\left\{\begin{matrix}\left[(\mathbf{H}_z)_{q^+}^{n+1/2} - (\mathbf{H}_z)_{q^-}^{n+1/2}\right]/\Delta y - \\ \left[(\mathbf{H}_y)_{r^+}^{n+1/2} - (\mathbf{H}_y)_{r^-}^{n+1/2}\right]/\Delta z\end{matrix}\right\}}{\left[1 + \Delta t\sigma_p/2\varepsilon_p\right]},
\end{aligned} \tag{4}$$

where the superscripts $n + 1/2$ and n are the time stepnumbers; a group of changes (i,j,k) and Δt are the time steps; Δx, Δy, Δz are the distances of the adjacent lattice point in the x, y, z directions, respectively. Other field quantities can be treated in the same manner.

To perform a stable numerical simulation, the variables should satisfy

$$v_{\max}\Delta t \le \frac{1}{\sqrt{(1/\Delta x)^2 + (1/\Delta y)^2 + (1/\Delta z)^2}}, \tag{5}$$

where $v_{\max}$ is the maximum phase velocity, Δt denotes the time step, and Δx, Δy, Δz are the distance steps in the x, y, z directions, respectively. When $\Delta x = \Delta y = \Delta z = \Delta$, (5) can be simplified as $v_{\max}\Delta t < \Delta/\sqrt{3}$. To reduce the error caused by numerical dispersion effects, (5) should also satisfy the conditions $\Delta/\lambda_{\min} < 1/10$, where $\lambda_{\min}$ is considered the shortest wavelength of the electromagnetic wave considered.

The FDTD method was used to solve the numerical analysis problems presented by grating-patterned etching on the metallic silver film. This approach also enables the excitation of SPs and application of the total internal reflection dissipation field for exciting the SPs. The changes in time step Δt reflect the variations in energy flow on the receiving surface. This reflection is realized by placing a receiving surface over the structure. The changes in energy flow facilitate the analysis of the effects of structural parameter variations on the light extraction efficiency of LEDs.

3. Physical LED Model

The physical model of the LED with a double-grating displacement structure was constructed by grating-patterned etching on the GaN and metallic silver film surfaces (Figure 3). The model comprises the silver film layer, P-GaN layer, active layer, N-GaN layer, and SiC substrate. During the experiment, the calculated area dimensions of 4200 nm × 420 nm were realized; the thicknesses of the P-GaN and N-GaN layers were 200 and 400 nm, respectively. Compare with the physical LED model as described in [17], a grating-patterned etching was added to the GaN surface, which had two reasons. (1) Grating-patterned etching can diminish part of the total internal reflection produced by incident light. (2) A portion of the light causes the evanescent field of total internal reflection to excite SPs; The study in [7] has discussed that grating-patterned etching on the top surface can effectively enhance the light extraction efficiency of LEDs; thus, this phenomenon results in a combined effect with

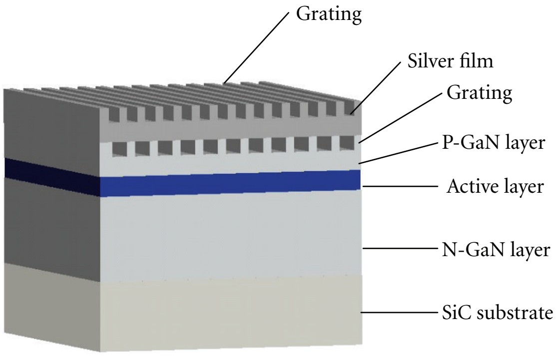


Figure 3: Physical model of an LED with a double-grating displacement structure.

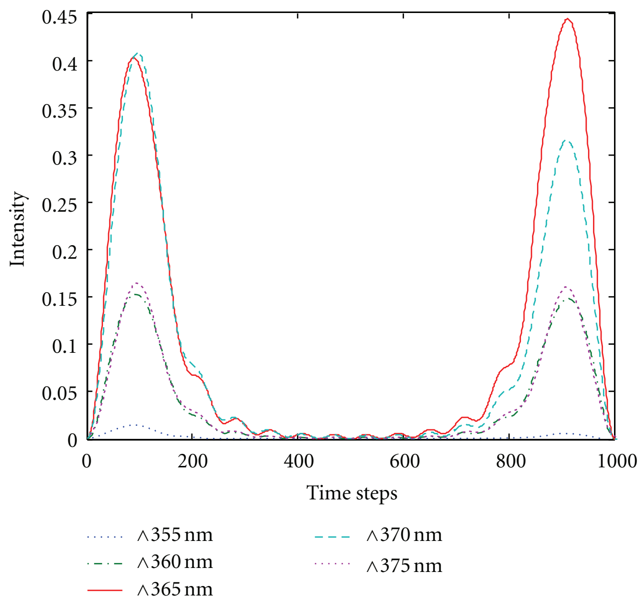


Figure 4: Energy flow of GaN at different grating periods.

grating-patterned etching on the metallic silver film surface, thereby enhancing optical transmission and improving the light extraction efficiency of LEDs.

4. Numerical Simulation and Analysis

A numerical simulation was conducted using the FDTD method. The wavelength of light was 500 nm, the refractive index of air was 1.0, and the refractive index of GaN was 2.4. The silver film was used in the Lorentz dispersion model. In analyzing the light absorption process, the silver film is disregarded. The light emitted by the active layer is replaced by the total field-scattered field source, an approach that realizes incident plane waves from all directions. The intensity was 1 and the grating period of the metallic silver film was 375 nm. A receiving surface, which is capable of reflecting light intensity, was placed above the model to keep track of energy flow.

4.1. Effect of Grating Period on the Light Extraction Efficiency of the GaN Surface. Figure 4 presents the energy flow of the GaN with a double-grating displacement structure at different grating periods. The maximum flow intensity value was 0.44, which can be obtained at a GaN surface grating period of 365 nm. Figure 5 shows the relationship between the surface grating period of GaN and light extraction efficiency when the silver film thickness changes from 300 nm to 400 nm. For light extraction efficiency with oscillatory changes in grating period, the maximum value acquired constantly ranged from 360 nm to 380 nm. This result confirms that grating period influences the light extraction efficiency of LEDs. At a silver film thickness of 300 nm to 400 nm, the relationship curves of grating period and light extraction efficiency are similar and the maximum light extraction efficiency occurred at a 365 nm grating period. When the grating period continued to increase, the light extraction efficiency gradually declined. This result is attributed to two factors. First, the surface grating period is related to the wave vector that causes plasmon resonance. Thus, only when the grating period satisfies the excitation conditions can the SPs be excited. Consequently, visible light is extracted and transmissible light is enhanced. Second, the ideal size of diffraction grating satisfies the wavelength of light on a metal surface when the period is considerably smaller than the wavelength of light. Otherwise, conductivity to light diffraction is low and the effect of changing light directions caused by light diffraction decreases. On the other hand, when the period is far from the wavelength of light, the plane of the grating section is excessively large, thereby causing stronger total internal reflection, which slows down light emission.

4.2. Effect of Silver Film Thickness on Light Extraction Efficiency. The grating period was set at 365 nm on the basis of the analysis in Section 4.1. The thickness of the metallic silver film was set at 300 nm to 400 nm. Figures 6 and 7 show the energy flow of the silver film with a double-grating displacement structure and that of the silver film with a single grating, respectively. The light extraction efficiency of LEDs with a double-grating displacement structure improved by 43% over that of the silver film surface with a single grating. The graph shows that the silver film thickness should satisfy the grating coupling conditions to enhance light extraction efficiency. A silver film that is too thick or too thin cannot induce coupling. The plasmon resonance mode existed on both sides of the metal/dielectric material interface. Thus, when the film thickness was at the nanometer scale, the evanescent field formed by the SPs was strong enough to pass through the other side of the metal. Consequently, the SP electromagnetic fields on both sides of the metal film interacted with each other and formed a group of coupled SPs, as illustrated by the energy flow curve of silver thickness at 390 nm in Figure 6.

The plasmon resonance frequency reached the same value and energy flow intensity reached a maximum of 0.55.

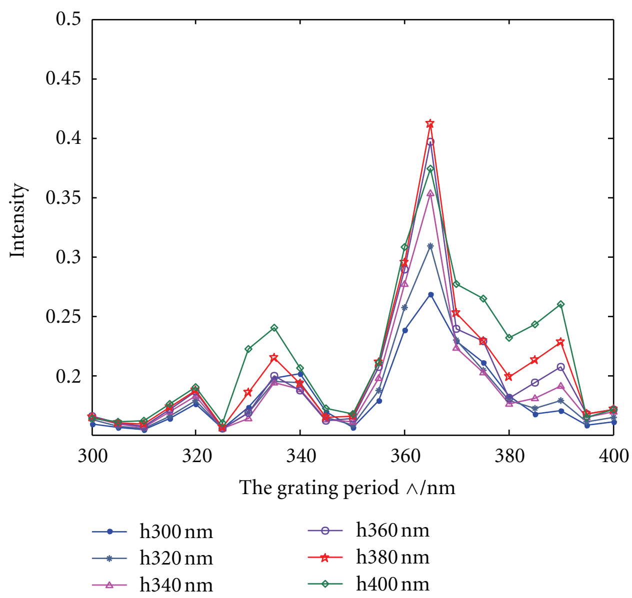


Figure 5: Relationship between the grating period of GaN and light extraction efficiency with silver film thickness ranging from 300 nm to 400 nm.

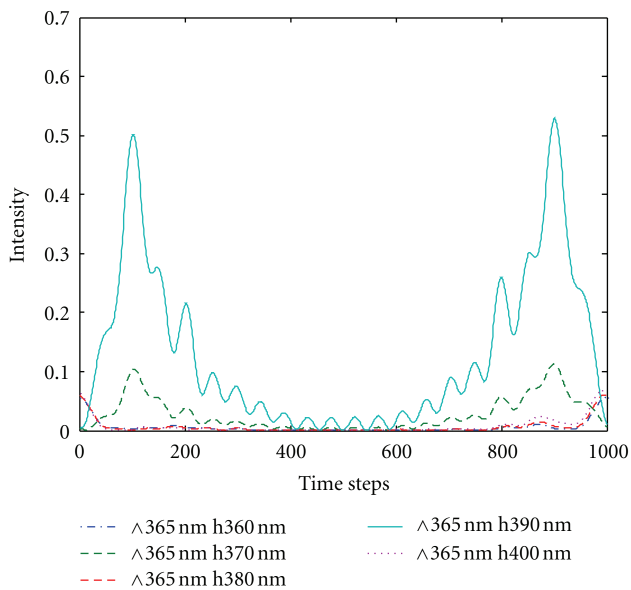


Figure 6: Energy flow of silver film (of different thicknesses) with a double-grating structure.

However, when the silver film thickness was smaller than 390 nm, the SP resonance frequency remained at the degenerate state, in which the energy flow intensity exhibited no significant enhancement. The results indicate the absence of a coupled phenomenon. With increasing silver film thickness, the energy flux rate gradually decreased, indicating the continuous division of the SP resonance frequency. Consequently, coupling disappeared when the silver film thickness tended toward infinity.

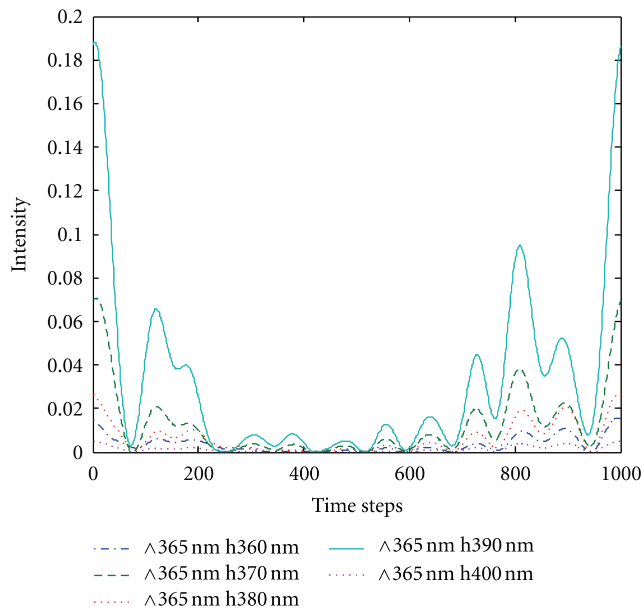


Figure 7: Energy flow of silver film (of different thicknesses) with a single grating structure.

5. Conclusion

Grating-patterned etching was performed on GaN and silver film surfaces to establish an LED model with a double-grating displacement structure. The FDTD method was used in conducting a numerical simulation. A grating etched on the GaN surface effectively extracts a limited amount of light and enhances the light extraction efficiency of LEDs. At a GaN grating period of 365 nm and a silver film thickness of 390 nm, light extraction efficiency reaches a maximum of 55%.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant no. 61107039 and no. 61004050 and the Natural Science Foundation of Heilongjiang Province under Grant no. F201006.

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The Scientific World Journal
Volume 2012, Article ID 395629, 6 pages
doi:10.1100/2012/395629

The ScientificWorldJOURNAL

Research Article

Estimating Elasticity for Residential Electricity Demand in China

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Received 28 July 2012; Accepted 27 August 2012

Academic Editors: C. Bin, T. Han-Song, and C. Zhan-Ming

Residential demand for electricity is estimated for China using a unique household level dataset. Household electricity demand is specified as a function of local electricity price, household income, and a number of social-economic variables at household level. We find that the residential demand for electricity responds rather sensitively to its own price in China, which implies that there is significant potential to use the price instrument to conserve electricity consumption. Electricity elasticities across different heterogeneous household groups (e.g., rich versus poor and rural versus urban) are also estimated. The results show that the high income group is more price elastic than the low income group, while rural families are more price elastic than urban families. These results have important policy implications for designing an increasing block tariff.

1. Introduction

Since the open and reform policy initiated in 1978, China has managed to maintain rapid economic growth and emerged as the second largest economy in the world. In line with the rapid economic expansion of the past three decades, electricity demand has been growing substantially. Between 1980 and 2009, electricity consumption in China increased from 3,006 TWh to 37,032 TWh, at an annual rate of 8%. Over this period, residential electricity demand grew at a faster rate of 12%. The share of residential consumption over total electricity consumption went up from 3.5% in 1980 to 13.1% in 2009. However, China's per capita residential electricity consumption is still much lower than that of developed countries, accounting for about one-fifteenth of that of the US and one-seventh of that of Japan [1]. Given the continuing trend in income growth, modernization, and urbanization, growth in residential electricity demand is expected to remain high in China.

In the past, China's electricity industry has relied on making massive investments and increasing supply to meet the fast growing demand. The installed power capacity increased from 5.7 million kw in 1978 to 900 million kw in 2010. However, as the problems, such as energy security and environmental deterioration, become more and more severe in China, increasing energy supply is becoming more costly. To promote energy conservation and reduce the local pollutants and carbon emissions, the Chinese central government has set the national energy intensity reduction target for two consecutive five-year plans, which are 20% and 16% for the 11th and 12th five-year plans (FYPs), respectively. To reach this goal, some policies must be instigated.

Given the side effects of supply policies, demand policies have been taking increasingly important roles in controlling electricity demand. Price policy, among these tools, has a particular role to play in energy conservation. In a competitive market, a rational agent would optimally reduce energy consumption in response to a higher price. However, China's energy sector is still heavily regulated by the government. Electricity pricing is completely controlled by the government. As pointed out by Lin and Jiang [1], China's residential electricity consumption is subsidized by industrial consumption and, thus, the residential tariff is even lower than the production costs. The twisted price signal encourages overconsumption and leads to a deterioration in the environment since most of China's electricity is generated by coal. Raising the residential electricity tariff to better reflect the real cost (both production costs and external costs) and to reduce the cross subsidy becomes more and more urgent as the electricity market reform moves forward.

The policy effects of raising electricity tariffs are multifold. On one hand, raising electricity tariffs is believed to be an important measure to promote energy conservation and reduce emission. On the other hand, raising electricity tariffs will inevitably affect the welfare of the household, with differentiated effects on different social groups, such as rich versus poor or urban versus rural households. Quantitatively evaluating these policy effects needs good estimates of price and income elasticities of demand for electricity. Moreover, good estimates of price and income elasticities of demand for electricity are critical input parameters for many research studies. For example, the simulation results and subsequent conclusions of the computable general equilibrium (CGE) model, which is a popular analysis tool for evaluating energy and environmental policies, critically depends on the quality of the various energy demand elasticities.

Although estimating electricity elasticities has attracted much research effort since the first energy crisis of the 1970s, most of them focus on developed counties. J. Espey and M. Espey [2] reviewed 36 studies modeling residential electricity demand, among which only six studies focused on developing countries. Estimation of electricity elasticities based on rigid econometric analysis in China is especially scarce. The only study we found is that of Qi et al. [3], which estimated the price and income elasticities of residential electricity demand to be −0.15 and 1.06, respectively, using provincial level data between 2005 and 2007.

In this paper, price and income elasticities of Chinese residential electricity consumption are estimated for the first time based on data of a unique household survey. We specify the household electricity demand as a function of local electricity price, household income, and a number of social-economic variables (such as household size, age, and education of the household head and dwelling size). The objective of undertaking such estimation is to understand more deeply the key factors that influence electricity demand at household level in China.

We contribute to the literature in two aspects. First, to the best of our knowledge, this is the first paper that uses microlevel data to estimate the electricity demand elasticity in China. Aggregate level electricity consumption data are often employed to estimate electricity demand (e.g., among many other studies, [4–7]). However, the aggregate level data often lose much information at the individual level. Using microlevel data can better reflect the individual or household behavior and adds more details to our understanding of the consumers' response [8]. Second, we estimate the electricity elasticities across different heterogeneous household groups (e.g., rich versus poor and rural versus urban). This information contributes to the ongoing debate on how China's electricity market reform will affect different social groups and help design the new pricing scheme.

The rest of the paper is organized as follows. Section 2 describes the empirical models we employed and is followed by the data and estimation results presented in Section 3. In Section 4, the results are discussed and conclusions are given.

2. Residential Demand for Electricity

2.1. Basic Model. Residential demand for electricity is a demand derived from the demand for a well-lit house, cooked food, hot water, and so on and can be specified using the basic framework of household production theory [5]. According to the theory, households purchase input factors to produce the final goods, which appear as arguments in the household's utility function. In our specific case, a household combines electricity and capital equipment to produce a composite energy commodity.

Following the specification of [9, 10], a linear double-logarithmic form using income, electricity price, the price of alternative fuels, and a number of socioeconomic factors as independent variables is used in the empirical analysis of household electricity demand as follows:

$$\begin{aligned} \ln E_{it} = {} & \beta_0 + \beta_1 \cdot \ln\left(\mathrm{PE\_res}_p\right) + \beta_2 \cdot \ln(\mathrm{Income}_{it}) \\ & + \beta_3 \cdot \ln\left(\mathrm{PE\_ng}_p\right) + \beta_4 \cdot \mathrm{Z}_{it} + \varphi_t + \eta_{it}, \end{aligned} \tag{1}$$

where E_{it} is electricity usage for household i at year t. $\mathrm{PE\_res}_p$ is residential electricity price in province p, where household i lives. Income_{it} is real income of household i at year t. $\mathrm{PE\_ng}_p$ is real price of liquefied natural gas in province p, which may be a complement to or substitute for electricity for households. Z_{it} is a set of control variables, including household dwelling area (HSIZE_{it}), number of family members (FSIZE_{it}), the age (AGE_{it}), and years of education (EDU_{it}) of the household head. φ_t is the year-fixed effect.

The key explanatory variables that influence household electricity demand are thus described in the model above. Household income and electricity price are two important economic variables that are assumed to determine household electricity demand. Since we adopt the double-logarithmic specification, the parameter estimates of β_1 and β_2 can be directly interpreted as price and income elasticity.

Since electricity is not the only energy source for a household, electricity demand can also be influenced by the price of other alternative fuels. Therefore, we include the price of natural gas in the estimation of the demand functions. These are also included in the model in order to test the hypothesis of whether these fuels are in anyway complementary to or substitutes for electricity.

Several variables that represent household characteristics are included in the estimation model to account for the impact of the underlying preference of consumers of different backgrounds: (HSIZE_{it}), number of family members (FSIZE_{it}), the age (AGE_{it}), and years of education (EDU_{it}). We expect that a family which has more members or whose dwelling has a larger area may consume more electricity. How the age and education level of the household head will influence electricity consumption is an empirical question. The year-fixed effect is controlled to eliminate national trends, such as business cycles, that may affect household electricity demand.

2.2. Heterogeneous Effects. Residential electricity consumption may have different patterns among households which have different incomes or live in urban or rural areas. We examine these two heterogeneous effects by estimating (2) and (3) as follows:

$$\begin{aligned}\ln E_{it} = {} & \theta_0 + \theta_1 \cdot \ln\left(\text{PE\_res}_p\right) \times \text{Rich}_{it} \\ & + \theta_2 \cdot \ln\left(\text{PE\_res}_p\right) + \theta_3 \cdot \text{Rich}_{it} \\ & + \theta_4 \cdot \ln\left(\text{PE\_ng}_p\right) + \theta_5 \cdot Z_{it} + \varphi_t + \varepsilon_{it},\end{aligned} \tag{2}$$

where Rich_{it} is a dummy variable which equals one if the income of household i in year t is greater than the sample median. The interaction term between $\ln(\text{PE\_res}_p)$ and Richit captures the difference in price elasticity of the rich compared with the poor. Taking the poor household as the benchmark, the price elasticities of the poor household and the rich household are estimated by the coefficients θ_2 and $(\theta_1 + \theta_2)$, respectively. Consider the following:

$$\begin{aligned}\ln E_{it} = {} & \gamma_0 + \gamma_1 \cdot \ln \text{PE\_res}_p \times \text{Urban}_{it} \\ & + \gamma_2 \cdot \ln \text{Income}_{it} \times \text{Urban}_{it} + \gamma_3 \cdot \ln \text{PE\_res}_p \\ & + \gamma_4 \cdot \ln \text{Income}_{it} + \gamma_5 \cdot \text{Urban}_{it} + \gamma_6 \cdot \ln \text{PE\_ng}_p \\ & + \gamma_7 \cdot Z_{it} + \varphi_t + \varepsilon_{it},\end{aligned} \tag{3}$$

where Urban_{it} is the dummy variable for urban households. Similarly, the interaction terms between the price/income variables and the urban dummy variable capture the differences in price and income elasticities of urban households compared with rural households.

2.3. Estimation Issues. Econometrically estimating the electricity demand function presents several challenges. First, simultaneity problems exist between marginal price and consumption if aggregated data are used or consumers face a nonlinear price scheme because there is reverse causality between demand and price. Fortunately, the simultaneity problem is avoided in our study since we use the household level data in which the household is clearly the price taker. In addition, electricity prices have been highly regulated in China and local sales prices were set by provincial governments based on the costs of power generation, transmission, and distribution. The increasing block tariff did not start nationwide until July, 2012. During our study period (2008-2009), consumers faced the single price scheme, which enabled us to avoid the endogeneity problem caused by the nonlinear pricing scheme. Second, energy demand is influenced by long-term household decisions over appliance purchases and dwelling characteristics. Some studies have used a system of equations where the household makes two-stage optimization decisions. In the first stage, the short-run consumption of electricity depends, among other variables, on electricity price and income. In the second stage, the purchasing decision for durable goods, such as electronic appliances, is modeled [11, 12]. Since the system of equations approach has a very high data requirement (information on holdings of household-specific appliances and residence features), single equation specifications for household energy demand are most often used in linear or logarithmic form [13–17].

There are several options for estimating (1)–(3): pooled OLS, which assumes away significant individual or temporal effects among the panel; the fixed effects or random effects models, which assume there are unobserved specific individual and temporal effects. As introduced above, electricity price has been highly regulated in China. During our study period, the prices were quite uniform within a province and remained stable over years. A lack of variation in the price variable forced us to adopt the pooled OLS technique.

3. Data and Estimation Results

3.1. Data. The household level data used in this study is provided by the China Family Panel Studies (CFPS) project, conducted annually by Peking University of China since 2008. In 2008 and 2009, the survey was carried out in Beijing, Shanghai, and Guangdong, which are located in eastern China. Stratified random sampling is applied, which ensures representativeness and randomness. A more detailed description of the CFPS project can be found in Hvistendahl [18]. The CFPS survey data contain information on various aspects of the household, such as socioeconomic information and demographic status, education information, and health information of the households. The CFPS survey data have been employed in a number of studies, such as Luo and Zhang [19] on health and labor market outcomes and Su and Heshmati [20] on gender wage difference.

A panel dataset is constructed using CFPS 2008 and 2009. In 2008, the survey covered 2,375 households, among which 1,940 households were followed up in 2009. Keeping the families that are observed in both years and with nonmissing electricity usage, the balanced panel covers 1,649 households.

Descriptive statistics are reported in Table 1. In our dataset, the average electricity consumption per capita is 37.78 kWh per month, which is 37% higher than the national average of 27.66 kWh per month [21]. (The average electricity usage for each household is 112.97 kWh per month in our dataset. On average there are 2.99 household members. So each person consumes 37.78 kWh per month.) This is because Beijing, Shanghai, and Guangdong, where the data were collected, are among the most developed provinces of China. As introduced above, a single price scheme for residential electricity was implemented in China during our investigating period. The nominal electricity prices in 2008 and 2009 for Beijing, Shanghai, and Guangdong remained unchanged at 0.47, 0.54, and 0.61 Yuan/KWH, respectively. The prices of electricity and natural gas are deflated using the provincial consumer price index (CPI).

3.2. Estimation Results. Columns (2)–(4) of Table 2 report the estimation coefficients and associated t-values for the three electricity demand models ((1)–(3)) based on the household data using the OLS technique. In model 1, the own price elasticity of electricity demand is estimated to

Table 1: Descriptive statistics of the household survey data.

Variable	Description	Obs.	Mean	Std. dev.	Min.	Max.
E	Electricity usages (KWh/family/month)	3,298	112.97	88.65	0	550
Income[a]	Household income (Yuan)	3,298	37,239.13	43,856.17	0	33,8000
HSIZE[a]	Dwelling area (m^2/family)	3,298	92.20	70.45	0	800
FSIZE	Family size (person/family)	3,298	2.99	1.33	1	12
PE_res	Residential electricity price (Yuan/KWh)	3,298	0.56	0.06	0.49	0.62
PE_ind	Industrial electricity price (Yuan/KWh)	3,298	0.82	0.04	0.76	0.89
PE_ng	Natural gas price (Yuan/m^3)	3,298	6.12	0.62	5.50	7.29
Age	Age of household head	2,072	59.04	13.19	17	95
Edu	Years of education of household head	2,704	8.21	4.36	1	19

Note: [a]For income, HSIZE, age, and edu, we replace missing values with 0 and create missing indicators for missing observations. Missing indicators are controlled for in the following regressions.

Table 2: Estimation results using OLS technique.

	Model 1: basic	Model 2: income effect	Model 3: urban versus rural
	Dependent variable: ln(residential electricity consumption)		
ln(PE_res)	−2.477***	−2.638***	−3.735***
	(0.374)	(0.493)	(0.492)
ln(Income)	0.058***	0.016**	0.063***
	(0.005)	(0.007)	(0.009)
ln(PE_ng)	−0.486**	(0.252)	0.304
	(0.247)	(0.258)	(0.246)
ln(HSIZE)	0.162***	0.103***	0.159***
	(0.021)	(0.030)	(0.029)
FSIZE	0.068***	0.069***	0.099***
	(0.013)	(0.013)	(0.012)
Age	0.002	0.000	−0.005***
	(0.001)	(0.001)	(0.001)
Edu	0.064***	0.052***	0.030***
	(0.004)	(0.005)	(0.003)
ln(PE_res)*Rich		0.482	
		(0.661)	
Rich		0.201	
		(0.291)	
ln(PE_res)*Urban			2.644***
			(0.652)
ln(Income)*Urban			−0.040***
			(0.011)
Urban			(0.240)
			(0.307)
Year FE	Y	Y	Y
	OLS	OLS	OLS
Observations	3298.000	3298.000	3298.000
R-squared	0.160	0.186	0.239

Note: Robust standard errors in parentheses; $^{***}P < 0.01$, $^{**}P < 0.05$, $^{*}P < 0.1$.

be −2.477, which carries the expected sign and is statistically significant at the 1% level. This suggests that a 1% increase in residential electricity price would result in a more than 2% decline in household electricity demand (ceteris paribus). The result implies that households are very responsive to electricity price changes. Electricity consumption is responsive to the level of income with an income elasticity of 0.058. However, since elasticity is well below unity, income growth results in a much less than proportional increase in electricity consumption.

An examination of the coefficient on the price of natural gas that is included in the model provides the cross elasticity between electricity and natural gas. The estimated coefficient is −0.486 and marginally significant. The result implies that there is a weak complementary relationship between electricity and natural gas, which reflects that electricity and natural gas have largely independent uses and limited switching. A similar complementary relationship between electricity and natural gas has been found for California residents [22] and Indian residents [23].

As we expected, larger dwelling size and more family members increase the household consumption of electricity. A 1% increase in the number of square meters results in about a 0.162% increase in the household's demand for electricity, while increasing the family number by one results in a 6.8% increase in the household demand for electricity (ceteris paribus).

Finally, the demographic characteristics may also influence the electricity consumption of the household. A one-year increase in the period of education results in a 6.4% increase in electricity consumption (ceteris paribus).

In model 2, we add a dummy variable that represents relatively rich families and associated interaction terms to control for the effect of income difference on electricity demand and the estimation results are reported in column 3 of Table 2. As indicated above, the estimated coefficient of the interaction term ln(PE_res)*Rich can be interpreted as the difference in price responsiveness of electricity demand between the rich household and poor household. The estimated coefficient is small and statistically insignificant, which means that the rich family and the poor family respond similarly to electricity price changes. The estimated coefficients of other variables in model 2 remain stable compared with model 1.

In model 3, we add a dummy variable that represents whether the family lives in an urban area or a rural area and the associated interaction terms controlling for the effect of living location on electricity demand. The estimation results are reported in Column 4 of Table 2. The price elasticity for rural and urban households is −3.735 and −1.091, respectively, while the income elasticity is 0.063 and 0.023, respectively. These results indicate that urban residential electricity consumption is less elastic to both price and income. The estimates provide supportive evidence that urban household electricity consumption is less sensitive to price and income changes. Raising electricity price will be more detrimental to rural families. The income increase of the rural households will lead to more residential electricity demand. However, the overall effect is mild.

4. Conclusions

The paper provides the results of the econometric estimation of the electricity demand model using a dataset consisting of information at the individual household level in China. The basic model is used to determine the responsiveness of electricity consumption to its own price, income, price of alternative fuel, and variables relating to the social-economic characteristics of the household. The estimated models demonstrate the importance of including the household level information, which is impossible using aggregate level data. Demand elasticities for the heterogeneous household level are also examined.

We found that residential demand for electricity responds rather sensitively to its own price in China. There might be two reasons to explain the seemingly high estimate of our study. First, the estimates of electricity price elasticity depend on the model specification and data. Taylor [24] reviewed many studies and found electricity to be much more price elastic in the long run. Our estimated results, using a pooled two-year dataset and OLS technique, are consistent with his conclusion. Second, China's economy has undergone rapid development and modernization during the past 30 years. Most Chinese residents have experienced the dramatic change from lacking the basic living necessities before the 1980s to, today, being able to afford the costly electrical appliances (such as air conditioners, shower heaters, and washing machines) which represent the modern life style. However, for the Chinese, the virtue of thrift and the preference to save have hardly changed. It could be expected that an increase in the price of electricity might result in many households cutting back the use of electric appliances, for instance, they may choose to wash their clothes by hand, instead of using a washing machine, or to turn on the air-conditioner for only a few hours on a hot day instead of running it all day. Supportive evidence is that high estimates of the price elasticity of residential electricity demand were found in studies in the US before the 1970s [25, 26] and in some developing countries or regions, such as Taiwan [27] and Honduras [28].

From the policy point of view, the high price elasticity of residential electricity demand implies that there is the potential to use the price instrument to conserve electricity consumption. Electricity pricing schemes, such as the increasing block tariff, seasonal pricing, and/or residential time-of-use pricing, will increase the overall electricity price level and thus can effectively curb the demand of the electricity.

Since July 1st, 2012, China has begun to implement the increasing block tariff nationwide. How to design an effective tariff structure to ensure that the new pricing scheme can improve efficiency and equity is an essential question. The keys to the increasing block tariff design include the number of blocks and the volume and price in different blocks. The examination of the electricity demand elasticity of different groups shows that the high income group is more price elastic than the low income group, while rural families demonstrate more price elasticity than urban families. These results have three implications for designing the increasing block tariff. First, to ensure equity and satisfy the basic needs of consumers, the electricity volume of the first block should be set large enough to cover the usage of most residents. Second, the price of the last block, which targets the high income households, should be set high to ensure an effective cut in consumption. Third, since our results also show that raising electricity prices will be more detrimental to rural families, it is necessary to separate the rural and urban households and design different volumes and prices in each block for each group.

Finally, as would be expected, the estimates for income elasticities show that electricity is a necessity. The relatively low value of this elasticity means that residential electricity consumption would grow moderately with further growth in the Chinese residents' incomes.

Acknowledgment

The research support from the funds of Renmin University of China (11XNL009) is gratefully acknowledged.

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The Scientific World Journal
Volume 2012, Article ID 692746, 13 pages
doi:10.1100/2012/692746

The ScientificWorldJOURNAL

Research Article

Exergetic Assessment for Resources Input and Environmental Emissions by Chinese Industry during 1997–2006

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Received 20 June 2012; Accepted 10 July 2012

Academic Editors: C. Bin and C. Zhan-Ming

This paper presents an overview of the resources use and environmental impact of the Chinese industry during 1997–2006. For the purpose of this analysis the thermodynamic concept of exergy has been employed both to quantify and aggregate the resources input and the environmental emissions arising from the sector. The resources input and environmental emissions show an increasing trend in this period. Compared with 47568.7 PJ in 1997, resources input in 2006 increased by 75.4% and reached 83437.9 PJ, of which 82.5% came from nonrenewable resources, mainly from coal and other energy minerals. Furthermore, the total exergy of environmental emissions was estimated to be 3499.3 PJ in 2006, 1.7 times of that in 1997, of which 93.4% was from GHG emissions and only 6.6% from "three wastes" emissions. A rapid increment of the nonrenewable resources input and GHG emissions over 2002–2006 can be found, owing to the excessive expansion of resource- and energy-intensive subsectors. Exergy intensities in terms of resource input intensity and environmental emission intensity time-series are also calculated, and the trends are influenced by the macroeconomic situation evidently, particularly by the investment-derived economic development in recent years. Corresponding policy implications to guide a more sustainable industry system are addressed.

1. Introduction

The natural resources depletion has been considered as one of the main constraints for sustainable development [1, 2]. Resources, especially nonrenewable resources, are required to supply the basic human needs and to improve the quality of life [3]. At the same time, a majority of nonrenewable resources are consumed in the industry sector, which provides most energy and matter used in modern society. Resources production and consumption by industrial activities are therefore reckoned as a strong positive determinant ingredient of air pollution and climate change [4].

In China, the industry sector accounts for approximately 70% of the total energy resources input and consumes the largest amount of mineral resources such as iron ores in the world [5]. Industrial activities along with huge resources input and low resource use efficiency have engendered striking environmental emissions such as greenhouse gases (GHG). Averagely, 81.4% of SO_2, 80.9% of soot, and 47.8% of waste water in China were emitted by the industry sector during 1997–2006 [6]. In the year of 2006, 24.0 billion ton industrial waste water, 22.3 million ton SO_2, and 13.0 million ton solid waste were discharged into the environment. The share of CO_2 emissions from the industry sector accounted for more than two-thirds of China's total energy-related CO_2 emissions [7]. During a period of rapid economic growth in China, the challenge confronted with the industry sector is the ever-increasing pressure on natural environment due to large amounts of nonrenewable resources consumption with urgent regard for environmental consequences.

Without explicit throughput measures, the scale question of the physical resource base and human conditions cannot be analyzed and reflected adequately [8, 9]. An efficient understanding of the resources use and environmental impact of the Chinese industry against drastic socioeconomic transitions demands systematic biophysical assessment with a unified measure. Exergy is defined using thermodynamics principles as the maximum amount of work which can be produced by a system as it comes to equilibrium with a reference environment [10–12]. The potential usefulness or ability to perform work for a natural resource is its exergy content [13, 14], and then exergy quantifies the quantity and quality scarcities of diverse resources effectively [15]. Distinguishing from the traditional economic analysis, exergy accounting provides a unified way to measure different materials and energy with solid scientific basis [15, 16] and provides a wide and clear vision of the use and degradation of energy and subsequently of natural resources [17, 18]. As an overall and unifying assessing tool, exergy analysis has been widely employed to evaluate the resources use at different scales [19–23], and particularly to perform the resource exergy analysis of different countries [16, 24–40].

Meanwhile, uses of exergy are increasing in fields related to environmental impact. All utilization of resources and disposal of waste products affect nature and the effect is strongly related to the amount of exergy in the utilized resource or the disposed waste [11, 19, 41]. The exergy amount of an emission is the physicochemical work absorbed by the environment in order to equilibrate the substances of the emission with the standard environment [42]. All emissions have definable, calculable, and additive exergy contents with respect to the defined reference environment, and then exergy can be regard as a suitable unifying measure of environmental emissions. Rosen and Dincer [43–45] further stressed that the exergy embodied in waste emissions represents a potential for environmental change. The concept of exergy has been gradually accepted as a "direct" measure or at least as a proxy stated by Ayres [46] for the potential environmental impact of waste emissions [41, 42, 47–50].

Closely relevant to exergy-based insight into resources use and environmental impact of the Chinese industry, Chen and his fellows have carried out a series of studies in their social exergy analysis of resources use and environmental emissions at the national scale covering the industry sector [38–40, 50, 51]: Chen and Qi [38] presented systems account for the resources exergy utilization of China society 2003; G. Q. Chen and B. Chen [39] provided an extend-exergy analysis of the resources conversion and waste emissions of the China society in 2005; Zhang and Chen [40] provided an exergy-based systems account for the resources use and environmental emissions (including GHGs and "three wastes") of China society 2006; Zhang et al. [50] provided a chemical exergy-based unifying assessment of the "three waste" emissions by Chinese industry during 1997–2006. However, the overall status and trend of the resources use and environmental impact by Chinese industry remain to be revealed systematically with an objective measure to quantify and evaluate various resources and wastes in more aggregated levels.

The aim of this paper is to present an exergetic assessment for the resources input and environmental emissions of the Chinese industry during 1997–2006. By accounting the fundamental utility of resource inflows into Chinese industry including fossil fuels, mineral resources, agricultural and forest products, and other industrial raw materials based on a unified measure, resources use of the Chinese industry is elucidated. Meanwhile, environmental impact of the Chinese industry and in particular, main environmental emissions covering GHGs and "three wastes" are evaluated. Exergy intensities in terms of resource input intensity and environmental emission intensity time-series are also calculated. Corresponding discussion and policy implications coupled with China's macroeconomic situation are presented. In sum, insights provided by exergy analysis in this study can be added to the poor knowledge between industrial economic profitability and ecological sustainability and contribute to resources management and environmental regulation for the policymakers in China.

2. Methodology and Data Sources

2.1. System Boundary and Data Sources. Chinese industry refers to the material production sector which is engaged in the extraction of natural resources and processing and reprocessing of minerals and agricultural products [6], including (1) extraction of natural resources, such as mining and salt production (excluding hunting and fishing); (2) processing and reprocessing of agricultural products, such as rice husking, flour milling, wine making, oil pressing, silk reeling, spinning and weaving, and leather making; (3) manufacture of industrial products, like steel making, iron smelting, chemicals manufacturing, petroleum processing, machine building, timber processing; water and gas production, and electricity generation and supply; (4) repairing of industrial products such as the repairing of machinery and means of transport (including cars).

For the national-scale system, the resources input into the Chinese industry contains the imported, gathered, constrained, and extracted commodities as exergy carriers [15, 16]. For avoidance of repetitive and cross calculations, the entrance boundary points are set at the same level of the exergy inflow. Most of relevant environmental resources and economic data for the mainland China are adopted or derived from the official databases and public issued official statistical yearbooks, such as Almanac of China Paper Industry [52], China Environment Yearbook [53], China Food Industry Yearbook [54], China Industrial Economic Statistical Yearbook [55], China Steel Yearbook [56], China Yearbook of Nonferrous Metal Industry [57], and Statistical Yearbook of China [6].

2.2. Exergy Methodology. In this study, all the thermal exergy of the materials are neglected, for the difference between the temperatures of the materials and the environment is small and therefore the thermal exergy is much less than the chemical exergy of the materials according to the basic definition of exergy [38]. Extensive illustrations for estimating exergy coefficients for different resources in China have been provided by B. Chen and G. Q. Chen [30] and Chen and Qi [38]. Concrete exergy coefficients of the accounted resources are listed in Table 1.

Table 1: Exergy coefficient of various resources.

Item	Exergy coefficient	Unit	Source
Fossil fuels			
Coal	22.16	PJ/Mton	[38]
Oil and oil product	44.32	PJ/Mton	[38]
Natural gas	4.13	$PJ/10^8$ cu·m	[38]
Minerals			
Iron ore (55% Fe)	0.46	PJ/Mton	[38]
Iron ore fine (70% Fe)	0.84	PJ/Mton	[38]
Sulphur iron ore (35% S)	9	PJ/Mton	[38]
Copper ore (0.65% Cu)	0.03	PJ/Mton	[30]
Lead ore (3.5% Pb)	0.02	PJ/Mton	[30]
Zinc ore (5.9% Zn)	0.05	PJ/Mton	[30]
Copper ore fine (23.8% Cu)	1.1	PJ/Mton	[38]
Alumina (63.7% Al)	2	PJ/Mton	[38]
Phosphorite (25% P_2O_5)	0.1	PJ/Mton	[38]
Raw salt (NaCl)	0.2	PJ/Mton	[38]
Limestone	0.01	PJ/Mton	[30]
Metal scraps			
Steel (Fe)	6.8	PJ/Mton	[38]
Copper (Cu)	2.1	PJ/Mton	[38]
Aluminum (Al)	32.9	PJ/Mton	[38]
Forest products			
Wood	10	PJ/Mton	[30]
Bamboo	18.67	PJ/Mton	[58]
Turpentine	37.4	PJ/Mton	Calculated by authors
Oil-tea camellia seed	35.3	PJ/Mton	Calculated by authors
Tung oil	38.9	PJ/Mton	Calculated by authors
Agricultural products			
Sugarcane	5	PJ/Mton	[38]
Cotton	16.4	PJ/Mton	[30]
Hemp	16.35	PJ/Mton	[30]
Rapeseed	37	PJ/Mton	[30]
Beet	5	PJ/Mton	[30]
Soybean	3.9	PJ/Mton	[30]
Cocoon	4.5	PJ/Mton	[30]
Wool	3.7	PJ/Mton	[30]
Peanut	24.6	PJ/Mton	[30]
Sesame	23.4	PJ/Mton	[30]
Tubers	3.7	PJ/Mton	[30]
Bean	3.9	PJ/Mton	[30]
Rice	15.56	PJ/Mton	[30]
Wheat	15.4	PJ/Mton	[30]
Corn	8.6	PJ/Mton	[30]
Tobacco leaf	10.7	PJ/Mton	[30]
Pork	25	PJ/Mton	[30]
Beef	11.5	PJ/Mton	[30]
Mutton	16	PJ/Mton	[30]
Poultry	4.5	PJ/Mton	[30]
Milk	4.9	PJ/Mton	[30]
Egg	6.2	PJ/Mton	[30]
Fruit	1.9	PJ/Mton	[30]

Table 1: Continued.

Item	Exergy coefficient	Unit	Source
Aquatic product	5.77	PJ/Mton	[30]
Straw	14.3	PJ/Mton	[30]
Other raw materials			
Pulp	17	PJ/Mton	[30]
Rubber	32.48	PJ/Mton	[30]
Synthetic rubber	45.53	PJ/Mton	[59]
Ethylenc glycol	19.34	PJ/Mton	[60]
Terephthalic acid	24.8	PJ/Mton	[60]
Polyethylene in primary forms	48.26	PJ/Mton	[60]
Polypropylene in primary forms	47.7	PJ/Mton	[59]
Polystyrene in primary forms	50.2	PJ/Mton	[60]
Polyvinyl chloride in primary forms	20.35	PJ/Mton	[59]

Note: The exergy coefficients of water potential energy and nuclear energy were deduced from their product of electricity (0.36 PJ/10^8 kWh) with the transformation factor of 1.17 and 3.51, respectively [38]. Some chemical materials, nonmetallic mineral, and other raw material are not included due to their negligible exergy input or scarcity data.

Table 2: Exergy coefficient of various emissions.

Item	Exergy coefficient	Unit	Source
CO_2	0.45	PJ/Mton	[60]
CH_4	51.98	PJ/Mton	[60]
COD	13.6	PJ/Mton	[40]
SO_2	4.9	PJ/Mton	[60]
Soot	3.5	PJ/Mton	[50]
Dust	1.5	PJ/Mton	[50]
Solid waste	0.5	PJ/Mton	[50]

As to the emission account for the industry system as a macroeconomy, it is reasonable to adopt a global standard environment model to resemble the atmosphere, ocean and earth's upper crust with average geophysical chemical characteristics as the reference environment [60, 61]. The chemical exergy of an emission, as the dominant exergy component is considered in this paper. In China, industrial environmental emissions were not covered in statistics until 1997, and the environmental statistic items only cover the main emissions of the conventional "three wastes." We extract all the available data for the period from 1997 to 2006 and chose the most remarkable environmental emissions to do a trend analysis. Owing to the data availability, seven major emissions (i.e., CO_2, CH_4, COD, SO_2, soot, dust, and solid waste) are included in our calculations. The emission data of CO_2 and CH_4 are taken from Zhang [62] and other emission data from the official published statistical yearbooks [53]. Detailed exergy coefficients of the accounted emissions are presented in Table 2.

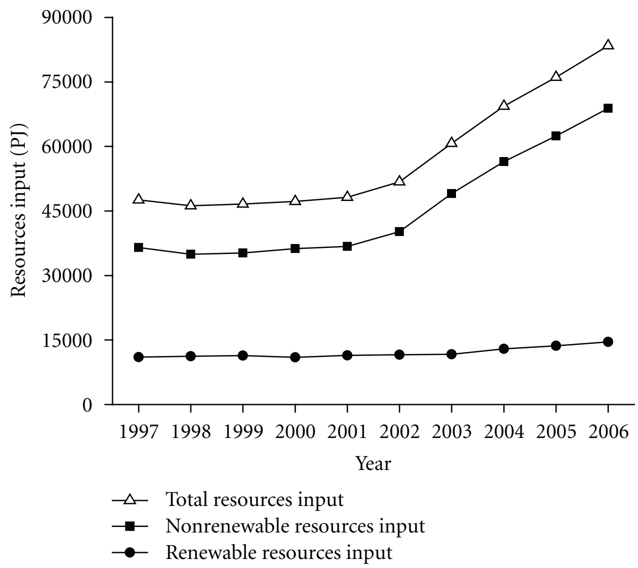

Figure 1: Resources input by Chinese industry.

3. Results

3.1. Resources Input. As the sum of all input fluxes outside the system boundary, a detailed exergy accounting for the resources input of the Chinese industry is performed. Compared with 47568.7 PJ in 1997, resources input in 2006 increased by 75.4% and reached 83437.9 PJ. Concretely, the input of resources exergy kept steady around 46196.5–48187.9 PJ during 1997–2001; while afterwards, it increased from 51777.7 PJ in 2002 to 83437.9 PJ in 2006, with an average annual growth rate of 12.7%. Two categories of resources input are divided, that is, nonrenewable and renewable resources, with corresponding results of exergy accounting shown in Figure 1. The greater part of resource inflows into the industry sector were seen to come from nonrenewable resources, which accounted for 75.6%–82.5% of the total. A rapid increment of the nonrenewable resources input in the recent 5 years can be found, from 40183.3 PJ in 2002 to 68878.6 PJ in 2006, owing to the increasing input of raw coal, crude oil, natural gas, metal and nonmetal minerals into the industrial subsectors. Details are shown in Table 4.

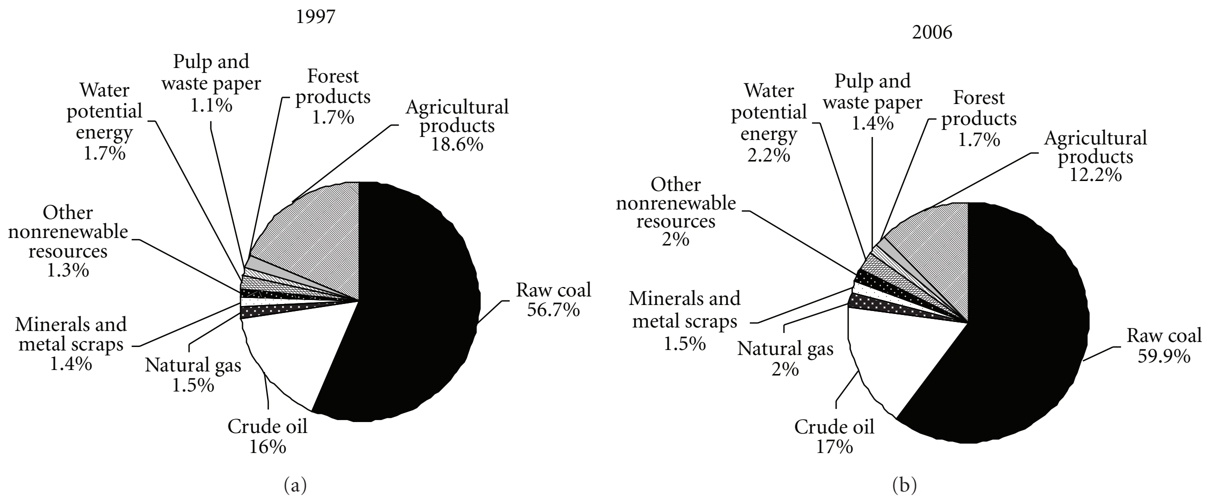

Figure 2: Components of resources input by Chinese industry in 1997 and 2006.

Of all the nonrenewable resources, coal inflow was the largest, contributing to 52.4%–59.9% of the total resources input. In particular, the coal input decreased from 26962.3 PJ in 1997 to 25175.5 PJ in 2001, which can be contributed to rectification and readjustment of coal production performed to balance the wide gap between the supply and demand [16]. During 1998–2001, 58000 small village coal mines were shut down and their production capacity with 2.7×10^8 ton was stopped [63]. Since 2002, the coal production rebounded, restored and continued to increase due to the rapid rise of coal consumption and electricity demand. The input of crude oil also increased 1.9 times in 2006 of that in 1997 and accounted for averagely 18.0% of the total resources input over this period. Natural gas input amounted to 1709.7 PJ, 2.5 times of that in 1997. The iron ore and scrap steel resources input in iron and steel industry increased by 178.7% in the past decade, from 359.5 PJ in 1997 to 1001.9 PJ in 2006. Particularly, the imported iron ore fine and steel product rose rapidly and amounted to 400.0 PJ in 2006, compared with 136.2 PJ in 1997. Nonferrous ores and scrap resources input had increased by more than 3.9 times from 35.4 PJ in 1997 to 136.0 PJ in 2006. As the primary raw material for the cement industry, limestone also expanded 2.4 times during the past ten years.

Only a small part of resource inflows from renewable resources, for example, within agriculture and forestry, were used in the industry sector. Renewable resources inflows increased by 31.9% from 11041.4 PJ in 1997 to 14559.2 PJ in 2006, owing to the increasing input of water potential energy, the grains and meats into the food processing industry, and other industrial materials (e.g., wood, pulp, and waste paper). For instance, water potential energy input increased rapidly from 830.0 PJ in 1997 to 1845.7 PJ in 2006, and the imported wood and bean rose by 585.6% and 816.7% in 2006, respectively. Totally, the share of renewable resources in the total resources input decreased from 23.2% (11041.4 PJ) in 1997 to 17.4% (14559.3 PJ) in 2006. Detailed components of resources input by Chinese industry in 1997 and 2006 are shown in Figure 2.

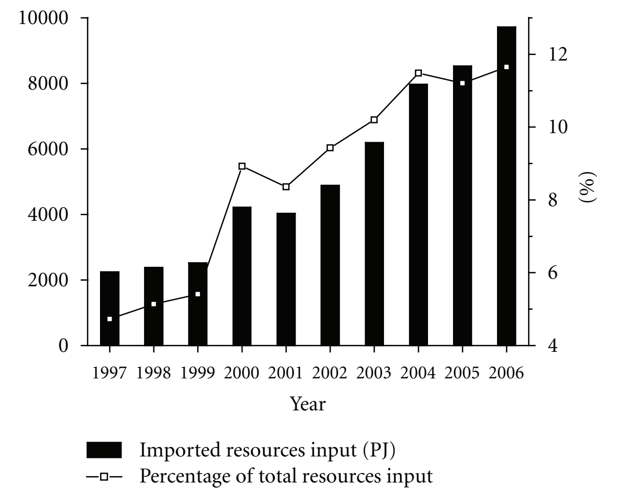

Figure 3: Imported resources input by Chinese industry (Note: Right y-axis refers to percentage of total resources input).

Furthermore, the domestic supply of energy and mineral resources always cannot meet the huge and ever-increasing demands in China, and then a large amount of industrial raw materials need to be imported. The total amount of imported resources input into the Chinese industry increased rapidly from 2249.9 PJ (4.7% of the total resources input) in 1997 to 9720.9 PJ in 2006 (11.7% of the total), as shown in Figure 3. As the largest imported resource, crude oil accounted for 67.2% of the total imported resources input for the period between 1997 and 2006 on average.

Resource input intensity (RII), as the ratio of the total exergy input of resources to the total industrial value added (IVA), is a critical parameter for resource policies that aims to reduce resource consumption while maintaining or even boosting economic growth. The lower the ratio, the fewer the resources input to yield per unit IVA and the higher macroeconomic efficiency of resources use in the industrial economy. Macroeconomic output of the Chinese industry

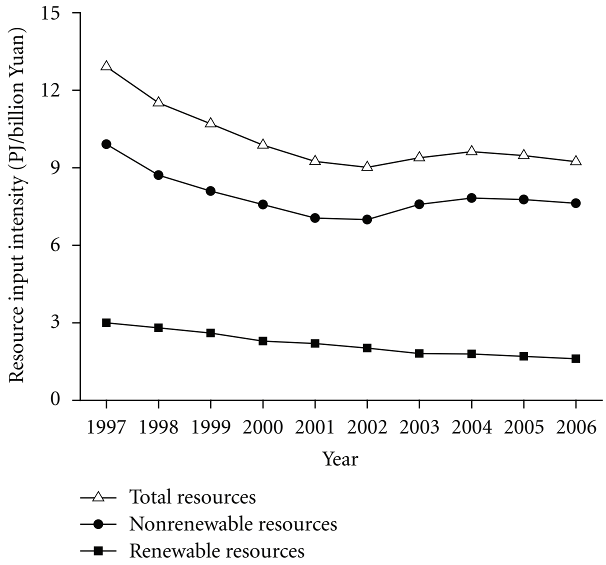

Figure 4: Resource input intensity by Chinese industry.

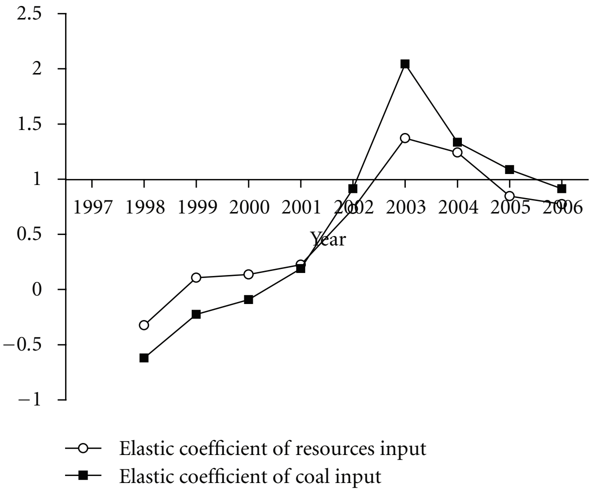

Figure 5: Elastic coefficients of resources input and coal input by Chinese industry.

along with a large amount of resources input has experienced spectacular uprising with 10.6% average annual growth rate in the total industrial value added (at 2006 constant price, similarly hereafter) over 1997–2006. Figure 4 presents the resource input intensity of the Chinese industry in this period. The total RII decreased from 12.9 PJ/billion Yuan in 1997 to 9.0 PJ/billion Yuan (1 US$ = 7.7087 RMB Yuan in 2006) in 2002. However, it started to increase by 6.8% over 2003-2004, and declined by 1.6% in 2005 and 4.1% in 2006. As noted previously, the nonrenewable resource input had the dominated share (75.6%–82.5%) in the total resources input. Then the trends of the nonrenewable resource input intensity and the RII show little difference, while the renewable resource input intensity decreased gradually during 1997–2006. Since fossil fuels are the largest resources input, energy intensity measured by the fossil fuels input (including coal, oil, and natural gas) per unit IVA is also calculated. During this period, the energy intensity decreased by 30.2% in 1997–2002, however it rose by 8.1% in 2003 or 11.7% in 2004 and then slightly declined by 2.3% over 2005-2006.

Displayed in Figure 5 is the resource input elastic coefficient (RIEC) measured by the ratio of the growth rate of resources input to the growth rate of industrial value added [64]. In the detail years, the growth of IVA was faster than the growth of total resources input during 1997–2002 with the average value of the RIEC 0.17; however, the growth of total resources input exceeded the growth of IVA in 2003 and 2004, and the RIEC reached 1.37 in 2003 and 1.24 in 2004; but the RIEC declined to 0.85 in 2005 and 0.77 in 2006. The drastic change of RIEC values is largely due to the change of fossil fuels input. Prominently, the elastic coefficient of resources input changed simultaneously with that of coal input during 1997–2006, as shown in Figure 5.

3.2. Environmental Emissions. Environmental emissions can be categorized into GHG emissions and "three wastes" emissions (i.e., waste water, waste gas, and solid waste) in conventional sense. Industrial environmental emissions in terms of GHG emissions and "three wastes" emissions in the past decade (1997–2006) are shown in Figure 6. The total exergy of environmental emissions by Chinese industry amounted to 2107.4 PJ in 1997; however, this figure rose by 66.0% and jumped to 3499.3 PJ in 2006. From the exergetic perspectives, higher exergetic value of the emission reflects the larger deviation in chemical composition from the reference environment and indicates its essential effect on environmental change. In exergy, the GHG emission dwarfs the "three wastes" emission by an order of magnitude and determined the trend of industrial environmental emissions in the whole period to a remarkable extent. In 2006, the total exergy of all the seven primary emissions in 2006 was estimated to be 3499.3 PJ, of which 93.4% was from GHG emissions and only 6.6% from "three wastes" emissions. A rapid growth of the GHG emissions took place for the period between 2002 and 2006, increasing from 1915.7 PJ in 2002 to 3267.2 PJ in 2006 with an average annual growth rate of 14.3%. Meanwhile, the total exergy of "three wastes" emissions did not change remarkably over 1997–2006.

Displayed in Figure 7 is a further comparison of the emission shares in 1997 and 2006. As the largest emission category, the share of the CO_2 emissions in the total emissions increased from 54.6% (1150.0 PJ) in 1997 to 65.8% (2302.5 PJ) in 2006, followed by the CH_4 emissions, contributing to 26.2% and 27.6% of the total in 1997 and 2006, respectively. As to the GHG emissions concretely, CO_2 emissions accounted for 67.6%–74.9% of the total GHG emissions and CH_4 emissions 30% on average in the past decade. It is worth noting that SO_2 and COD were the two main pollutants in "three wastes" emissions. The exergy of COD emissions of the Chinese industry decreased from 145.9 PJ in 1997 to 69.3 PJ in 2004, afterward it increased by 8.8% in 2005 and declined by 2.4% in 2006. Meanwhile, SO_2 emissions decreased by 15.7% in 1997–2002 and then increased rapidly from 76.5 PJ in 2002 to 109.5 PJ in 2006.

Table 3: The three components of GDP by expenditure approach.

Year	Final consumption expenditure Share (%)	Final consumption expenditure Contribution to the GDP growth (percentage points)	Gross capital formation Share (%)	Gross capital formation Contribution to the GDP growth (percentage points)	Net exports of goods and services Share (%)	Net exports of goods and services Contribution to the GDP growth (percentage points)
1997	37.0	3.4	18.6	1.7	44.4	4.2
1998	57.1	4.4	26.4	2.1	16.5	1.3
1999	74.7	5.7	23.7	1.8	1.6	0.1
2000	65.1	5.5	22.4	1.9	12.5	1.0
2001	50.0	4.1	50.1	4.2	−0.1	0
2002	43.6	4.0	48.8	4.4	7.6	0.7
2003	35.3	3.5	63.7	6.4	1.0	0.1
2004	38.7	3.9	55.3	5.6	6.0	0.6
2005	38.2	4.0	37.7	3.9	24.1	2.5
2006	39.2	4.3	41.3	4.6	19.5	2.2

Data source: [6].

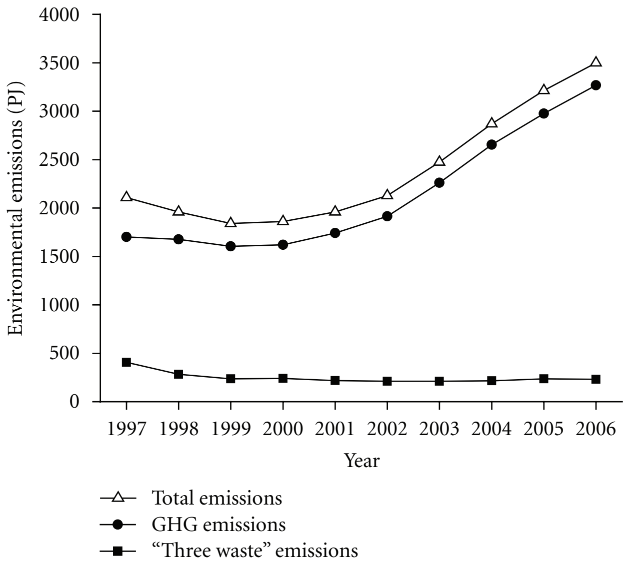

Figure 6: Environmental emissions by Chinese industry.

The emissions of soot, dust, and solid waste experienced a significant drop during 1997–2006. Detailed results of environmental emissions of the Chinese industry during 1997–2006 are shown in Table 5.

Environmental emission intensity (EEI) defined as the environmental emission exergy per unit of the total industrial value added indicates the environmental effect along with industrial economic output. The lower the EEI, the better environmental performance of industrial activities can be conducted. Figure 8 displays that the total EEI decreased from 0.57 PJ/billion Yuan in 1997 to 0.37 PJ/billion Yuan in 2002, and then fluctuated slightly during 2002–2006. The GHG emission intensity determined the trend of environmental emission intensity over this period to some extent, increasing its share from 80.7% (0.46 PJ/billion Yuan) in 1997 to 93.4% (0.36 PJ/billion Yuan) in 2006. It is worthy of noting that the time-series trend of the environmental emission intensity is in line with that of the resource input intensity, largely owing to the coal-dominated energy structure in China.

4. Discussion

It is worth noting that a majority of the industrial subsectors with high resources input level are the energy-intensive sectors. According to the China Energy Statistical Yearbook [65], the primary end-use energy consumption sectors in industrial system in 2006 were the manufacturing sectors, which accounted for 85.4% of the total industrial energy consumption. Among the manufacturing sectors, the sector of *Smelting and Pressing of Ferrous Metals* made up 25.8% of the total end-use energy consumption, followed by *Manufacture of Raw Chemical Materials and Chemical Products* with 14.9%, and *Manufacture of Nonmetallic Mineral Products* with 12.1% [65]. Correlation analysis shows that the correlation coefficients between mineral resource inflows into the iron and steel industry and energy resource inflows (i.e., coal, petroleum, natural gas) over 1997–2006 were higher than 0.9. Similar results can be found in the nonferrous industry.

China is adopting energy-intensive technology and investing the excessive expansion of high-energy consuming sectors, such as iron and steel, cement, and electrolytic aluminum. The outputs of main industrial products, especially most energy-intensive products, increased rapidly during 1997–2006. For instance, the outputs of crude steel, ten major nonferrous metals, motor vehicles, ethylene, cement, plate glass, electricity, chemical fiber, and primary plastic in 2006 were 3.9, 3.3, 4.6, 2.6, 2.4, 2.8, 2.5, 4.4, and 3.8 times of those in 1997, respectively [6, 55]. Some studies in energy intensity (measured by energy consumption with mass units per unit of GDP) reported that the primary driving force for the decline in China's energy intensity during 1997–2002 was efficiency effect rather than sectoral structural shifting [66–68]. It implies, therefore, that technical progress made a notable contribution in the industry during 1997–2002. However, since 2003, the industry sector has raised

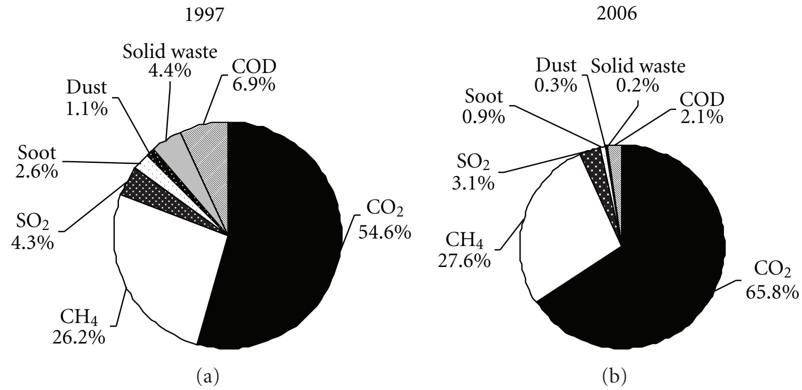

Figure 7: Components of environmental emissions by Chinese industry in 1997 and 2006.

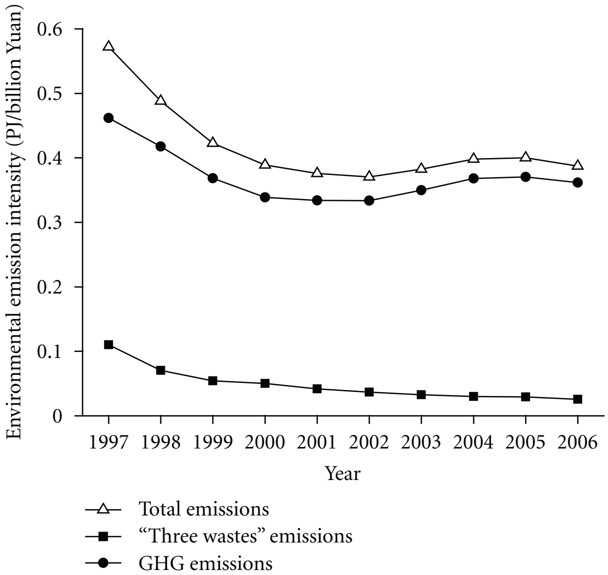

Figure 8: Environmental emission intensity by Chinese industry.

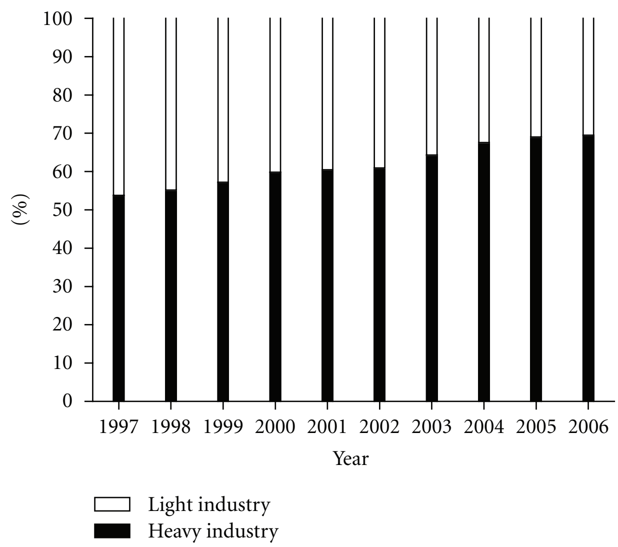

Figure 9: Component of the industrial value added by year.

its production levels and expanded energy-intensive subsectors rapidly. Liao et al. [69] also found that the excessive expansion of high-energy consuming sectors and the high investment ratio were foremost sources of the increasing energy intensity during 2003–2005. Figure 9 further shows that the heavy industry contributed the increasing share to the total industrial value added over 1997–2006 [6]. In 2006, the ratio of the industrial value added of heavy industry to that of light industry reached 70 : 30.

In fact, the resource utilization level in China still has large gaps in production process, technology, and management, compared with the international advanced level. The average resource extraction efficiency in China is lower than 20%–30% of the global advanced average [70]. As to the production process, the average energy consumption level of equipment and technology in China's manufacturing sectors is more than 10% of that in the OECD countries in general [71]. For instance, the overall energy consumption for per ton of steel, cement, oil refining, ethylene, and calcium carbide output in 2004 were higher than 15.6%, 23.3%, 53.4%, 59.6%, and 19.4% of those in the OCED countries, respectively [72]. The GDP energy intensity in China's industry is also distinctly higher than international levels. According to Yuan et al. [73], the average energy intensity for main products in eight industry sectors of electric power, oil, nonferrous metals, construction material, textile, and others is 40% higher than the world average. Therefore, the potential for promoting resource utilization level is substantial and urgent, especially in some resource-intensive or energy-intensive sectors. At the same time, the industry faces the tremendous challenges of limit resources supply in domestic reserves. It is well known that a large amount of industrial raw materials consumed in China comes from imported goods from the rest of the world. For instance, 50% of the domestic iron ore demand, 33% of alumina, 40% of crude oil, and 44% of wood in 2004 were met through international trade [63]. The pressure for seeking sustained resource supply and improving resource use efficiency is unprecedented.

Table 4: Resources input by Chinese industry, 1997–2006 (Unit: PJ).

Resource category	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Nonrenewable resources	36527.3	34953.4	35259.0	36264.4	36956.1	40183.3	49028.7	56466.1	62427.3	68878.6
Raw coal	26962.3	25473.4	24987.0	24759.4	25175.5	27521.6	34606.9	39917.9	44861.6	49979.4
Crude oil	7622.1	7633.0	8321.2	9330.3	9381.8	9908.8	10977.4	12686.8	13278.0	14218.5
Natural gas	697.6	708.3	744.2	834.3	899.5	939.6	1106.0	1212.6	1461.2	1709.7
Iron ores and scraps	359.5	344.1	337.1	359.7	411.3	466.7	572.4	703.4	855.1	1001.9
Nuclear energy	182.2	178.1	188.8	211.5	220.7	317.3	547.5	637.5	670.6	692.7
Nonferrous metal ores and scraps	35.4	32.3	34.9	57.0	47.1	66.8	79.2	106.3	128.3	136.2
Nonmetal minerals	247.8	128.7	121.9	101.6	95.8	100.9	97.3	136.9	127.4	136.0
Other nonrenewable resources	420.5	455.6	523.8	610.8	724.4	861.6	1042.0	1064.8	1045.1	1004.1
Renewable resources	11041.4	11243.2	11353.2	10984.2	11231.9	11594.5	11695.2	12928.6	13659.0	14559.3
Water potential energy	830.0	880.9	863.2	941.9	1174.9	1219.8	1201.6	1497.2	1681.5	1845.7
Pulp and waste paper	535.2	536.9	589.7	596.6	619.1	718.6	808.7	907.4	1022.8	1168.0
Forest products	831.5	835.1	798.9	795.0	818.0	924.8	1037.5	1124.3	1207.2	1382.2
Agricultural products	8844.6	8990.2	9101.3	8650.7	8620.0	8731.4	8647.5	9399.8	9747.5	10163.4
Total	47568.7	46196.6	46612.2	47248.6	48187.9	51777.7	60723.9	69394.7	76086.3	83437.9
Imported resources	2249.9	2374.5	2521.9	4216.6	4027.8	4882.7	6192.2	7967.1	8525.7	9720.9

Furthermore, the rapid growth of materials production and the energy demand for electricity and coal in some major industrial sub-sectors (e.g., steel, electrolytic aluminum, cements, and paper industry) with high-energy consumption and heavy environmental emissions determine the emission profile of the Chinese industry [50, 74–76]. The energy or raw materials utility subsectors are the major sources of industrial environmental emissions. For the period between 1997 and 2006, the sectors of electric power production and coal mining were the leading emitters of CO_2 and CH_4 among all the industrial subsectors, respectively [62]. The electric power production, iron and steel production, manufacture of nonmetallic mineral products, nonferrous smelting accounted for about 90% of industrial SO_2, soot and solid waste emissions in 2004 [77]. It is well known that the quantities of industrial GHG emissions and air pollutants in China are closely related with energy consumption, especially coal consumption [50, 74, 75]. Inefficient and coal-dominated energy production and consumption are at the core of China's environmental emissions. Along with the rapid growth of industrial value added and resources use, the total exergy of industrial "three wastes" emissions has seen a steady decline, though a slight increase of SO_2 and COD emissions in some years. This effect can be attributed to the effective emission control policies made by the central and local governments. However, GHG emissions of the Chinese industry increased rapidly along with a new rising period of Chinese economy since 2002. It is important to note that China's emissions control programs focus specifically on "three wastes" emissions rather than targeting at greenhouse gases such as carbon dioxide [78]. To tackle the problems of industrial environmental emissions, a more international way of thinking instead of a regional approach should be taken, with specially emphasis on the greenhouse gases rather than the regional pollutants merely [50].

Prominently, the resources use and environmental impact of the Chinese industry have been notably influenced by the macroeconomic situation in the last decade. Table 3 presents the three components of GDP by expenditure approach during 1997–2006. Totally, final consumption expenditure and gross capital formation shared the majority proportion of the GDP over this period. During 1998–2001, the economic growth was largely derived by the domestic demand. After 2002, the situation started to overturn: the contribution of gross capital formation in China's total GDP exceeded that of the final consumption expenditure. Investment has become an important motor for China's economic growth in recent years [76, 79]. Most of the investment flows into manufacturing, infrastructure, and real estate related sectors [80], which enormously pushes up the demand for certain resource- and energy-intensive products, such as steel, nonferrous metals, cement, glass, and machine. Since the second half year of 2003, the government had implemented a series measures to strengthen macro-control, with specially emphasis on the control of the investment in fixed assets, land supply management and environmental regulation [63]. There was significant decline in the growth rate of investment and total investment for new planned projects, especially heavy industry investment after 2005, while slight decline of resource input intensity and environmental emission intensity by Chinese industry over 2005-2006 can be found.

5. Concluding Remarks

Natural resources from the ecological system are required for producing and supplying goods and service in the industry system. Environmental emission assimilation as an additional ecological input into the industry sector can also be regarded as the use of an "ecological service." For sustainable

Table 5: Environmental emissions by Chinese industry, 1997–2006 (PJ).

Emission category	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
GHGs	1701.3	1676.0	1604.6	1620.8	1740.7	1915.7	2261.7	2653.5	2976.0	3267.2
CO_2	1150.0	1169.6	1178.5	1213.4	1259.5	1349.3	1582.3	1837.2	2077.9	2302.5
CH_4	551.4	506.4	426.1	407.3	481.2	566.4	679.4	816.4	898.2	964.7
Three wastes	406.1	283.1	236.0	240.5	218.2	211.4	212.0	215.4	236.9	232.0
SO_2	90.7	78.1	71.5	79.0	76.8	76.5	87.8	92.7	106.3	109.5
Soot	54.8	41.1	33.4	33.4	29.4	28.1	29.6	31.0	33.2	30.3
Dust	22.6	19.8	17.6	16.4	14.9	14.1	15.3	13.6	13.7	12.1
Solid waste	92.1	35.2	19.4	15.9	14.5	13.2	9.7	8.8	8.3	6.5
COD	145.9	108.9	94.1	95.8	82.6	79.4	69.6	69.3	75.5	73.6
Total	2107.4	1959.2	1840.6	1861.2	1958.8	2127.1	2473.8	2868.9	3212.9	3499.3

development, natural resources, especially nonrenewable resources should not run out and environmental emissions should not endanger the ecological system [40]. Given China's rapid industrial expansion, policy-makers require a more detailed understanding of the complex linkages between industrial activities and natural environment if the resultant resource use and environmental impact are to be minimized. In this paper, an exergy-based physical assessment is performed to measure the resources use and environmental impact of the Chinese industry for the period between 1997 and 2006.

The resources input into the Chinese industry reached 83437.9 PJ in 2006, and increased by 75.4% compared with that in 1997. For the time-series trend, resources input showed little variation during 1997–2001 and the initial trend had changed since 2002 with the input levels showing a great rebound. Nonrenewable resources accounted for 75.6%–82.5% of the total and determined the trend of resources input to a certain extent. A rapid increment of the nonrenewable resources input in the recent 5 years can be found, from 40183.3 PJ in 2002 to 68878.6 PJ in 2006 with an average annual growth rate of 14.5%. Coal input was the largest contributor, accounting for 52.4%–59.9% of the total resources input during the period, followed by crude oil and natural gas. The imported resources input increased its share from 4.7% of the total resources input (2249.9 PJ) in 1997 to 11.7% in 2006 (9720.9 PJ), mainly coming from crude oil import.

The environmental emissions by Chinese industry increased from 2107.4 PJ in 1997 to 3499.3 PJ in 2006. In exergy, the GHG emission dwarfs the "three wastes" emission by an order of magnitude and determined the trend of industrial environmental emissions in the whole period to a remarkable extent. The total exergy of all the seven primary emissions in 2006 amounted to 3499.3 PJ, of which 93.4% was from GHG emissions and only 6.6% from "three wastes" emissions. A rapid growth of total GHG emissions took place for the period between 2002 and 2006, increasing from 1915.7 PJ in 2002 to 3267.2 PJ in 2006 with an average annual growth rate of 14.3%. As the largest emission category, the CO_2 emissions increased its share from 54.6% of the total emissions in 1997 to 65.8% in 2006, followed by CH_4 emissions contributing averagely 26% to the total. The exergy of "three wastes" emissions did not change remarkably over 1997–2006, and SO_2 and COD were the two main pollutants.

Exergy intensities in terms of resource input intensity and environmental emission intensity time-series are calculated. The resource input intensity declined for the period between 1997 and 2002, but it started to increase over 2003-2004 and then declined slightly in 2005 and 2006. The environmental emission intensity in the whole period shows a similar trend. Moreover, the development of macroeconomic efficiencies of resources input and environmental emissions can be split into two main periods with different characteristics: the first period from 1997 to 2001 corresponding to a more notable improvement in resource and environmental efficiency; the second period from 2002 onwards with faster increased nonrenewable resources input into resource—or energy-intensive subsectors under slower yield of industrial value added. The excessive expansion of high-energy consuming industrial subsectors and the high investment ratio in the macroeconomic structure were foremost sources of the increasing exergy intensities. To obtain the industrial value added of one billion Yuan (129 million US$) in 2006, the resources input and environmental emissions by Chinese industry were estimated to be 9.2 and 0.4 PJ, respectively.

Industry plays an important role in Chinese economy. The contributions of industrial value added to the increase of the GDP in China reached 47.0%–58.3% and the shares in the GDP were around 40% during 1997–2006 [6], which means that China relied on manufacturing industry to an unusually great extent. Nevertheless, skyrocketing resources input and environmental emissions of the Chinese industry mean a surging and huge pressure into the ecosystem. The depletion of the resources brings on the economic increase, and the resulting wastes are returned to the environment where they induce environmental pollution and climate change. Also the development of the Chinese industry can hardly become more resource and energy intensive that it is now, along with the limited resource reserves and adverse environmental quality. Therefore, increasing GDP based on traditional industrialization mode on the expense of natural environment is unsustainable. Continued strong emphasis on sustainability requires that future industrial economic growth must rely much more on environmental friendly and be less dependent on material products and natural resources than in the past. A large effort has to be made to promote industrial structure adjustment, strength resources management and resource efficiency improvement, rationalize resource prices, and implement more stringent energy saving and emission control policies. More importantly, the policies of restructuring and transformation of the resource-intensive economic growth pattern in China will affect and improve the whole situation of resources use and environmental impact of the industry sector.

Appendix

See Tables 4 and 5.

Acknowledgments

This study has been supported by the Humanities and Social Sciences Fund, Ministry of Education of China (Grant no. 12YJC790255), the Foundation of State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology (Grant no. SKLCRSM10KFA06), and the Fundamental Research Funds for the Central Universities (Grant no. 2011QG03).

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The Scientific World Journal
Volume 2012, Article ID 496341, 11 pages
doi:10.1100/2012/496341

The ScientificWorldJOURNAL

Research Article

Determinants of Electricity Consumption Intensity in China: Analysis of Cities at Subprovince and Prefecture Levels in 2009

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Received 10 May 2012; Accepted 27 May 2012

Academic Editors: C. Bin and C. Zhan-Ming

China has experienced great social and economic vicissitudes that caused the vast complexity and uncertainty for electricity consumption. This paper attempts to identify the main determinants of the electricity consumption intensity by using the data from Chinese cities at subprovince and prefecture levels in 2009. The key category factors, including urban morphology, industrial structure, regulation context, urbanization degree, price, natural condition, and resource endowment, are abstracted and the influence of these determinants is evaluated by adopting the finite mixture models. The variation of each determinant across regions, the comparative weights of all the factors, and the detailed classifications of the cities are reported for facilitating the understanding of electricity consumption in China. The corresponding policies for electricity administration are addressed as well.

1. Introduction

Industrialization and urbanization are two distinguishing features in the present social and economic development of China. The rural-to-urban migration and changes in industrial and economic structure are regarded as two major factors which determine the electricity consumption and economic output. The cities at subprovince and prefecture levels especially districts under the jurisdiction of cities which are, in general, cores of the region, play the leading roles and have the dominant positions in the processes of social development.

In the hierarchy of the administrative divisions of China mainland, cities at subprovince and prefecture levels (hereinafter briefly called the cities) cover 47.859% of China's total land area, 87.260% of total population, and 93.903% of Gross Regional Product (GRP), while 52.847% of GRP, 49.843% of total investment in fixed assets, and 51.695% of local government revenue are concentrated in the districts under the jurisdiction of the cities with only 12.476% of population and 27.654% of land area of the cities in 2009 [1, 2]. Meanwhile, the electricity consumption of the districts of the cities amounts to 1639.546 billion kwh which is about 44.273% of the total electricity consumption in China [2].

Prefecture level divisions (including subprovincial level, similarly hereinafter) are the second level of the administrative structure in the Constitution of China. The government at this level undertakes multiple responsibilities in terms of the administration of energy, economy, and environment issues.

The progress of urbanization and industrialization is always highly promoted by local governments, as it could bring about economic growth and better official performances which are two of the most important measures of GRP. Under the system of intergovernmental fiscal decentralization, about 52.400% of fiscal revenues are extracted by central government in 2009 [1]. The fiscal revenue of local government is another incentive to contest for output increase between different administrative divisions such as counties. As a general rule, the government at higher level is entitled to balance the development of the jurisdictional area. Hence the government at prefecture level is not only the implementer and promoter of urbanization and industrialization, but also the coordinator and participator of regional competition.

Table 1: Selected categorical indicators determined electricity consumption in the literature.

Reference	Regions	Contents	Period	Related variables	Categorical indicator
Larivière and Lafrance [23]	Canadian cities	Electricity consumption	1991	Urban density	Urban morphology
Halicioglu [29]	Turkey	Residential electricity consumption	1968–2005	Annual degree-days below 18°C Real residential electricity price Urbanization rate	Natural condition Price Urbanization
Bessec and Fouquau [34]	15 European countries	Electricity consumption	1985–2000	Temperature	Natural condition
Lai et al. [35]	Macao	Electricity consumption	2000–2006	Monthly mean temperature	Natural condition
Permana et al. [24]	Bandung city, Indonesia	Household consumption of electricity and liquefied petroleum gas	2007	Urban development forms	Urban morphology
Ziramba [32]	South Africa	Per capita residential electricity consumption	1978–2005	Real residential electricity price	Price
Liu [30]	China	Energy (including electricity) consumption	2009	Urbanization level	Urbanization
Aasen et al. [26]	Norway	Electricity consumption of enterprise	—	Electricity disclosure scheme	Regulation context
Bianco et al. [33]	Romania	Nonresidential electricity consumption	1975–2008	Electricity price	Price
Burke [36]	133 countries	Electricity ladder	1960–2003	Resource reserves	Resource endowment
Wiesmann et al. [31]	Portugal	Residential electricity consumption	2001	Heating /cooling degree-days Urbanization level	Natural condition Urbanization
Chen [27]	China	Energy (mainly electricity) conservation	2004–2011	Differential electricity pricing policy	Regulation context
Wang et al. [25]	China	Change in industrial electricity consumption	1998–2007	Change in industrial structure	Industrial structure

As a basic decision-making unit, the government at prefecture level is responsible for designing the layout of industry, especially that of small- and medium-sized enterprises (SMEs). For instance, the industrial park, being regarded as the incubator of local development, is often planned by government at this level. Meanwhile they also own the right to select industrial projects. In fact, the local government could reject the industrial settlement even programmed by the higher authorities for environmental or other reasons, or strive for it in order to earn more fiscal revenues when the projects are not settled. Thus the spatial arrangement of urban morphology and economy is mainly influenced and managed by authority at this level.

It is also a crucial node for the execution of energy policies including the regulation of electricity consumption in consideration of the more direct contact with local enterprises compared with higher authorities. The Chinese energy systems are intensively studied from the perspectives of international contexts [3, 4], provinces and regions [5, 6], macro systems [7–11], historical evolution [12, 13], and economic sectors [14, 15]. Further study focusing on the analysis of divisions at the prefectural level could provide detailed information on the enforcement of the energy legislation, the motivation for the behavior of local government, and the heterogeneity and exogenous variables determining the electricity consumption.

As an efficient method allowing introducing unobservable heterogeneity, which exists largely in Chinese regions due to the unbalance of development in terms of electricity consumption, the finite mixture model has been widely used for capturing the different effects among variables in regressions and segregating samples for the convenience of analysis. The application of finite mixture models includes Beard et al. [16] for the identification of the technical diffusion and changing among US banks, Wedel and Desarbo [17] for the clustering of market segment on the satisfaction study in Europe, Yau et al. [18] for the estimation of the effects of pertinent factors which influenced the hospital neonatal length of stay in Austria, and Imai and Tingley [19] for the measuring the performance of rival theories. Considering the possibility of inaccurateness caused by statistical mistakes of migration population and the consistency with China's statistical system, the electricity intensity defined as the ratio of electricity to GRP is used as the indicator of electricity consumption in different areas. This paper aims to abstract the key factors determining the electricity consumption intensity of the cities at prefecture level in China, evaluate the influence of the processes of urbanization and industrialization on the electricity consumption intensity, compare the difference of these determinants' impact, and understand the channels through which each variable functions for policy makers.

2. Literature Review

The determinants of electricity consumption are extensively studied in much of the contemporary literature. Overall, seven factors which attracted great attention considering the influences of economic, social, and geographic contexts can be classified, as shown in, Table 1.

Urban morphology refers to the characteristics of the spatial structure and the patterns of the regional economy. It is associated with many environmental topics as well, such as air pollution [20], land use [21], and urban conservation [22]. As for the electricity consumption, Larivière and Lafrance [23] demonstrated that raising the urban density which is defined as inhabitant per km^2 could decrease the annual city electricity consumption per inhabitant in Canada. Permana et al. [24] confirmed the differences of energy consumption per unit income in three kinds of urban forms in Bandung City which is selected as a typical sample of developing country cities.

Industrial structure refers to the number and size distribution of enterprises. It causes significant impacts on the distribution of electricity consumption. Wang et al. [25] decomposed the determinant factors influencing the change trend of industrial electricity consumption in China and characterized these elements. Besides, the economic output, as well as the social and environmental function of different sectors, should be taken into consideration from the systematic perspectives [10]. For instance, Xia et al. [14] introduced the employment variable to evaluate the Chinese industrial sectors.

Regulation context is related to the institution backgrounds of environmental legislation, administration structure, and other settings. Aasen et al. [26] analyzed the influences of the electricity disclosure scheme required by the EU Electricity Directive on Norwegian enterprises and found out that the regulation policy may be inefficient because of the malfunction of program implementation. Chen [27] described the reform process of electricity pricing system proposed by China's central authorities and presented three difficulties of the current promotion for the conservation of energy consumption. The administration powers from the higher authorities are the mainspring of promoting energy efficiency and conservation in China. The regulation of energy consumption relies heavily on mandatory plans or other compulsory measures from above due to lacking of market mechanisms [28].

Urbanization rate is measured by the ratio of urban population to the total population. Since the urbanized area does not only include megalopolises, metropolises, but also small cities and towns, urbanization is different from the concentration of population which gives more attention to the central point of the city. For instance, a person who is living in a small town which is far from the central city and undertaking the production of mechanical instruments should be regarded as the urbanization population but not as the people concentrated in the district of the city. Halicioglu [29] found the long-run causality relationship between residential electricity consumption and urbanization in Turkey. Liu [30] studied the linkage between urbanization and energy consumption based on econometric methods including ARDL testing and ECM methods and proposed that urbanization acceleration may harmonize the sustainable development in China. Wiesmann et al. [31] also use the urbanization as an explanation variable to model the residential electricity consumption.

Price is bound up with the electricity utilization in terms of the demand and supply of electricity. As the instrument of market adjustment, price scheme together with other factors such as urbanization rate [29] impacts the selection of energy type of the individual and enterprises and eventually determines the amount of electricity consumption. Ziramba [32] estimated the price and income elasticities of residential electricity consumption, showing the price insensitivity of electricity demand in South Africa. Bianco et al. [33] forecasted the nonresidential electricity consumption based on the price analysis using trigonometric grey model.

Natural condition is a set of factors which could affect the producing and living conditions and influences the demand function of electricity consumption as the independent variable. For example, the necessity of heating, ventilation, and air condition system in the building absolutely depends on the temperature and humidity. Bessec and Fouquau [34] found the nonlinear relationship between temperature and electricity consumption and distinguished different patterns of this link in European countries by virtue of panel threshold model. Lai et al. [35] modeled the electricity consumption in Macao using mathematic methods and identified the quadratic influence of temperature on electricity consumption. The significance of temperature impacts on electricity was also reported by Larivière and Lafrance [23] and Wiesmann et al. [31].

Resource endowment is associated with the reserves of mineral, water, and other resources in the region, exerting great influence on the selection and development of industry and indirectly determining the electricity consumption. Burke [36] found that the electricity ladder which is defined by the transition from traditional electricity to renewable power relied heavily on the energy endowments after the investigation of 133 countries.

3. Methodology and Data Descriptions

3.1. Finite Mixture Model and PCA. The finite mixture model would be employed to identify the complexity of the electricity consumption in China and scrutinize the influence of the key factors mentioned before. The integration of factor analysis and clustering with category indicators are provided for implementing the policies of electricity administration. Let y_i be the electricity consumption intensity (electricity consumption/GRP) observed for the city i, $i = 1, \ldots, N$. The sample is assumed to be drawn from a finite mixture model with K components. The probability density function for observations is given by

$$f\left(y \mid X_p, X_c, \Pi, \Theta, \alpha\right) = \sum_{l=1}^{K} \Pi_l(X_c, \alpha) f_l\left(y \mid \Theta\left(X_p\right)\right). \quad (1)$$

Here, X_p denotes the predictor vector, X_c is the concomitant variable vector, and f $(l = 1, \ldots, K)$ indicates the component density function with the parameter vector Θ. Π_l represents the component weight and is defined in the $(K-1)$-dimensional simplex as

$$\sum_{l=1}^{K} \Pi_l(X_c, \alpha) = 1, \quad 0 < \Pi_l(X_c, \alpha) < 1, \forall l, \quad (2)$$

where $\alpha = (\alpha_l')'_{l=1,\ldots,K}$ is the parameter vector determining the probability of components. Suppose further that the model is the mixture of Gaussian linear regression, and (1) could be constructed as

$$\begin{aligned} &\sum_{l=1}^{K} \Pi_l(X_c, \alpha) N\left(y \mid \mu_l\left(X_p\right), \sigma_l^2\right) \\ &\quad = \sum_{l=1}^{K} \Pi_l(X_c, \alpha) N\left(y \mid X_p' \beta_l, \sigma_l^2\right). \end{aligned} \quad (3)$$

Here $\mu_l(\cdot)$ is the mean with linear structure $\mu_l(\cdot) = X_p'\beta_l$ and σ_l^2 is the variance for the lth component normal density $N(y \mid \mu_l(X_p), \sigma_l^2)$. The coefficients of mixture regression β_l could be *fixed* across all the components, *nested* with some coefficients of components equally, or *varied* between the K components. Maximum likelihood (ML) estimation could be used to fit the multivariate Gaussian linear mixture models through the Expectation-Maximization (EM) algorithm [37–40]. In computation practices the component weight Π_l could be assumed to follow a multinomial logit model [41] as

$$\Pi_l(X_c, \alpha) = \frac{\exp(X_c'\alpha_l)}{\sum_t \exp(X_c'\alpha_t)}, \quad \forall l \quad (4)$$

with the constraint $\alpha_1 = 0$. Information criteria including Akaike Information Criterion (AIC) [42], Bayes Information Criterion (BIC) [43] and Hannan-Quinn Criterion (HQ) [44], and classification criteria including Normalized Entropy Criterion (NEC) [45], Classification Likelihood Criterion (CLC) [46] and Integrated Completed Likelihood-BIC (ICL-BIC) [47] are available for choosing the optimal structure of finite mixture models.

Principal component analysis, a linear dimension reduction method, is applied to combine the explanatory variables for the finite mixture model. This treatment was inspired by Bai and Ng [48] and Ng and Bai [49] and the analogous technique was also used in Xia et al. [14].

3.2. Data Descriptions

3.2.1. Data Definitions. As urban sprawl is generally developed from a specific focal point [50], the district concentration is a main feature of urban morphology. The district under the jurisdiction of the city is regarded as the focal point of the city, especially in China this district is normally the political, economical, and cultural center of the city. The concentrations of GRP (X_{11}), population (X_{12}), industrial value added (X_{13}), fiscal revenue (X_{14}), and investment in fixed assets (X_{15}) are selected for measuring *urban morphology* as defined in Table 2.

Table 2: Description of explanatory variables and category factors.

Variable	Description
Urban morphology[a]	
GRP concentration	The ratio of Gross Regional Product (GRP) of the district to that of the city
Population concentration	The ratio of population of the district to that of the city
Industrial concentration	The ratio of industrial value added of the district to that of the city
Fiscal concentration	The ratio of government revenue by the district to that by the city
Investment concentration	The ratio of total investment in fixed assets of the district to that of the city
Industrial structure	
Share of industrial output	The ratio of industrial value added to GRP in the city
Share of industrial employment	The ratio of the number of employed person in industry to the total of employed person in the city
Share of industrial electricity consumption	The ratio of electricity consumption in local industry to the total of energy consumption in the city
Regulation context	
Decease rate of energy intensity	The decease rate of energy consumption per unit of GRP in local province in the corresponding period
Decease rate of energy intensity of industry	The decease rate of energy consumption per unit of industrial value added in local province in the corresponding period
Decease rate of electricity consumption intensity	The decease rate of electricity consumption per unit of GRP in local province in the corresponding period
Urbanization rate	
Urbanization degree of the province	The proportion of urban population in the local province
Share of nonagricultural population	The proportion of nonagricultural population in the city
Urbanization degree of the city	The proportion of urban population in the city
Electricity price	
Average retail price of electricity	The weighted average of industry, commerce, and residence prices
Natural condition	
Annual average temperature	The mean of annual temperature according to urban temperature record in long term
Resource endowment[b]	
Ensured reserves of iron ore	The amount of iron ore that can be utilized under current conditions in the local province

[a]District refers to the districts under the jurisdiction of the city at subprovince and prefecture levels.
[b]The effects of ensured reserves of coal which had been also taken into account are not significant. The resource endowment of the city may be disturbed by the coal transportation, while the iron ore is often utilized locally in China.

The shares of industrial output (X_{21}), industrial employment (X_{22}), and industrial electricity consumption (X_{23}) are evaluated by the ratio of industrial value added to GRP, the ratio of industrial employment to total labor population and the weight of industrial electricity consumption in the city respectively. These indicators embody the aspects of economic, social, and environmental impacts and could give a comprehensive description of *industrial structure* (X_2).

The energy intensity and electricity consumption intensity are the main indicators to be supervised by Chinese energy regulatory system and official statistical bureau. The former one becomes a constraint target in national development programs such as the 12th Five-Year Plan; the latter would be easily monitored in the view of government authorities and also treated as a relatively accurate indicator to reflect the actual conditions of energy consumption due to fewer incentives to manipulate the data on electricity consumption in comparison with those on energy consumption. The decease rates of energy intensity (X_{31}), energy intensity of industry (X_{32}), and electricity consumption intensity (X_{33}) in the province are taken into consideration comprehensively to evaluate the regulation pressure which is exerted by provincial governments on the city authorities for the reflection of *regulation context* (X_3).

The urbanization rate of the province (X_{41}) is used to capture the provincial heterogeneity in the development due to uneven economic development in China. Since the urbanization process is often closely associated with the transfer of rural surplus labor to urban sectors, the share of nonagricultural population (X_{42}) is chosen to measure industrial dimension of urbanization. The combination of the urbanization rate of the city (X_{43}) and the other two variables could overcome the possible statistical bias coming from the incorrect estimated flowing population and gives a comprehensive evaluation of the categorical factor X_4, that is, *urbanization* (X_4).

Average retail price of electricity which is the synthesis of all kinds of price including residential price, commercial

Table 3: Descriptive statistics and units of original data.

Variable	Unit	Mean	Standard deviation	Minimum	Maximum
Output concentration (X_{11})	%	45.533	23.585	8.038	100.000
Population concentration (X_{12})	%	33.224	22.877	4.368	100.000
Industrial concentration (X_{13})	%	48.899	25.140	5.447	100.000
Fiscal concentration (X_{14})	%	52.600	25.490	5.931	100.000
Investment concentration (X_{15})	%	45.047	23.766	7.300	100.000
Share of industrial output (X_{21})	%	50.378	11.814	9.740	82.390
Share of industrial employment (X_{22})	%	45.419	15.178	6.550	79.450
Share of industrial electricity consumption (X_{23})	%	65.964	18.926	7.243	98.839
Decease rate of energy intensity (X_{31})	%	4.908	2.295	0.830	9.730
Decease rate of energy intensity of industry (X_{32})	%	8.984	3.057	0.030	15.100
Decease rate of electricity consumption intensity (X_{33})	%	5.330	0.812	2.810	6.970
Urbanization degree of the province (X_{41})	%	46.903	8.743	29.890	63.400
Share of nonagricultural population (X_{42})	%	61.423	25.211	13.480	100.000
Urbanization degree of the city (X_{43})	%	44.321	14.790	13.840	100.000
Average retail price of electricity (X_5)	Yuan/MWH	512.013	85.014	298.630	699.400
Annual average temperature (X_6)	°C	14.653	5.294	−1.880	25.500
Ensured reserves of iron ore (X_7)	100 million tons	9.916	16.698	0.000	70.200

Note. Some maximum values of concentration variables are 100% because of the fulfillment of urbanization in some region.

price, and industrial price in China is chosen as an integrative indicator to measure the factor *price* (X_5).

Since temperature is one of the most important factors affecting the electricity consumption as presented in literature, on account of the availability of data, annual average temperature which is recorded in climatological data is selected to measure the characteristics of *natural condition* (X_6).

In view of the dependence of manufacture industry in China's economic growth and the high growth in demand for mineral resource, ensured reserves of iron ore could be proxy for *resource endowment* (X_7).

3.2.2. Data Sources. The main data sources are China Statistical Yearbook and China City Statistical Yearbook, published by National Bureau of Statistics of China (NBSC). The variables associated with provincial characteristics are taken from NBSC [1] and those associated with city characteristics are abstracted from NBSC [2]. After removing the data with missing explanation variables, a final sample set of 277 cities including 15 cities at subprovince level and 262 cities at prefecture level in 2009 is obtained. The annual average temperature of each city is collected by the authors from public data sources such as the official website of local government. The average retail prices of electricity in the cities are drawn from the report of State Electricity Regulatory Commission [51].

3.2.3. Sample Description. The descriptive statistics and units of original data are given in Table 3. The great disparity between regions in China exists in consideration of concentration degree. The minimum values of concentration variables are below 10% while the maximum values of these reach to 100%, showing the spatial differences in Chinese urban development. The mean shares of industrial output, employment, and electricity consumption in industry are 50.378%, 45.419%, and 65.964%, respectively, indicating the high weight of electricity consumption in industry even if the output and employment contributions are accounted. Seeing that the average decease rate of industrial energy intensity (8.984%) is smaller than that of total energy intensity (4.908%) at the provincial level during the same period, the energy consumption of industry presents more elasticity than other sectors. The lowest retail price of electricity (298.630 Yuan/MWH) is only about 42.698% of the highest one (699.400 Yuan/MWH) in 2009. Despite the fact that the electricity price is regulated by Chinese government, price mechanism may play certain roles in resource allocations.

4. Results and Discussion

4.1. Dimensionality Reduction. Dimensionality reduction technique could provide crucial variables for understanding the key phenomena of interest without losing the information conveyed by the original data. The results of combined factors via PCA method could be given by

$$\begin{aligned} X_1 &= 0.977X_{11}+0.924X_{12}+0.935X_{13}+0.905X_{14}+0.955X_{15}, \\ X_2 &= 0.895X_{21} + 0.847X_{22} + 0.776X_{23}, \\ X_3 &= 0.493X_{31} + 0.841X_{32} + 0.927X_{33}, \\ X_4 &= 0.747X_{41} + 0.842X_{42} + 0.786X_{43}, \end{aligned} \tag{5}$$

The selected principle components of urban morphology (X_1), industrial structure (X_2), regulation context (X_3) and urbanization rate (X_4) extracted 88.242%, 70.724%, 60.356%, and 62.840% of squared loading sums, respectively.

Table 4: Estimation results and variable structure for the finite mixture model[a].

Variable	Structure	Coefficient estimates			
		Component 1	Component 2	Component 3	Component 4
		Predictor			
Intercept	Varied	5461.407*** (919.115)	379.656*** (87.482)	1774.662*** (158.055)	982.128*** (61.198)
X_1	Varied	113.915*** (40.749)	23.923*** (2.821)	59.830*** (6.378)	40.738*** (3.021)
X_2	Varied	66.189 (92.219)	22.124*** (6.895)	48.875*** (12.326)	32.844*** (4.232)
X_3	Fixed	−9.677** (4.896)	−9.677** (4.896)	−9.677** (4.896)	−9.677** (4.896)
X_4	Nested	19.305*** (7.366)	19.305*** (7.366)	17.365** (6.991)	17.365** (6.991)
X_5	Varied	−7.509*** (1.315)	−0.287 (0.185)	−2.910*** (0.414)	−0.759*** (0.130)
X_6	Varied	−52.716 (35.108)	6.815** (2.750)	25.498*** (7.160)	−7.531*** (1.774)
		Concomitant variable			
Intercept	Varied	—	2.187*** (0.441)	1.976*** (0.473)	2.285*** (0.516)
X_7	Varied	—	−0.032*** (0.012)	−0.062** (0.024)	−0.186** (0.092)

[a]The standard errors of coefficient estimates are in parentheses. ** and *** denote significance at 5% and 1% levels, respectively. All the explanatory variables are standardized.

4.2. Estimation Results. Considering the commonness of BIC [14, 49] and the robustness of ICL-BIC [47], the two criteria are used for appraising the fitting of mixture models. Table 4 shows the estimation results for the finite mixture model with best performance of fitting.

It is notable that the acting structure of factors that impacted on the electricity intensity is distinguishable across the components which are corresponding to the city clusters as shown in Table 5. The factors of urban morphology (X_1), industrial structure (X_2), price (X_5), natural condition (X_6), and resource endowment (X_7) present variance between components, while the influence of regulation pressure (X_3) is fixed and the impact of urbanization degree (X_4) shows a nest structure. Meanwhile, the factor of resource endowment (X_7) is modeled in the finite mixture model as a concomitant variable, indicating this factor influences the electricity intensity indirectly, whereas the other factors as predictors make more direct impacts on the dependent variable.

The estimations of each factor would be analyzed next. The positive coefficients on urban morphology (X_1) which is related to the urban concentration degree suggest that promoting the urban concentration would increase the electricity intensity. The moderate concentration of region would bring about economies of scale in the sense of electricity consumption, while the urban sprawling around a central point immoderately would vanish the scale merits and cause diseconomies of scale. The estimated results manifest the excess centralization of urban expansion in China. This centralized trend is most significant in the component 1 with the largest estimated coefficient which is evaluated *cluster 1* of cities.

The extent of industrial structure (X_2) impacts on electricity intensity is in keeping with that of urban morphology (X_1). That is, as for the electricity intensity, the higher marginal contribution of urban concentration means the greater marginal influence of the rise of industrial weights as viewed from the sizes of estimated coefficients between the categorical factors. It is the evidence that the highly centered development in regions is partially attributed to the significant dependence on industrial output. The combined function of these factors leads to the increasing of electricity intensity and the boost of electricity demand.

The estimated coefficients of −9.677 on regulation context (X_3) suggest that the administrative pressure from the higher level authorities on electricity consumption is the powerful measure to induce decreasing the electricity consumption intensity. Furthermore, as the estimation values are equal between the components, the validity of regulation pressure is identical across the cities owing to the homogeneity of administration system in China. The administration power from top to bottom is still a useful but expedient approach in the context of lacking long-term mechanisms for energy savings.

Regarding the urbanization rate (X_4), the impacts on electricity consumption intensity presented two levels as the coefficients of 19.305 and 17.365 illustrated. The variables are standardized before estimation, so the impact extents could be compared. The signs of estimates betoken the possibility of long-term increasing of energy consumption intensity due

Table 5: Clustering membership of the finite mixture model.

Cluster 1
Wuhai (Inner Mongolia), Anshan (Liaoning), Fushun (Liaoning), Benxi (Liaoning), Yingkou (Liaoning), Fuxin (Liaoning), Liaoyang (Liaoning), Huludao (Liaoning), Laiwu (Shandong), Jiaozuo (Henan), Panzhihua (Sichuan), Qujing (Guizhou), Tongchuan (Shaanxi), Jiayuguan (Gansu), Baiyin (Gansu), Shizuishan (Ningxia), Zhongwei (Ningxia)
Cluster 2
Shijiazhuang (Hebei), Handan (Hebei), Baoding (Hebei), Cangzhou (Hebei), Langfang (Hebei), Hengshui (Hebei), Jincheng (Shanxi), Shuozhou (Shanxi), Luliang (Shanxi), Hohhot (Inner Mongolia), Erdos (Inner Mongolia), Hulunbuir (Inner Mongolia), Bayannur (Inner Mongolia), Ulanqab (Inner Mongolia), Shenyang (Liaoning), Dalian (Liaoning), Dandong (Liaoning), Jinzhou (Liaoning), Panjin (Liaoning), Tieling (Liaoning), Chaoyang (Liaoning), Changchun (Jilin), Liaoyuan (Jilin), Baishan (Jilin), Songyuan (Jilin), Baicheng (Jilin), Harbin (Heilongjiang), Jiamusi (Heilongjiang), Wuxi (Jiangsu), Suzhou (Jiangsu), Nantong (Jiangsu), Lianyungang (Jiangsu), Yancheng (Jiangsu), Taizhou (Jiangsu), Suqian (Jiangsu), Zhoushan (Zhejiang), Hefei (Anhui), Wuhu (Anhui), Huangshan (Anhui), Chuzhou (Anhui), Bozhou (Anhui), Xuancheng (Anhui), Fuzhou (Fujian), Xiamen (Fujian), Putian (Fujian), Quanzhou (Fujian), Longyan (Fujian), Ningde (Fujian), Nanchang (Jiangxi), Jingdezhen (Jiangxi), Fuzhou (Jiangxi), Jinan (Shandong), Qingdao (Shandong), Zaozhuang (Shandong), Dongying (Shandong), Yantai (Shandong), Weifang (Shandong), Taian (Shandong), Weihai (Shandong), Dezhou (Shandong), Liaocheng (Shandong), Xuchang (Henan), Luohe (Henan), Zhoukou (Henan), Xiangfan (Hubei), Xiaogan (Hubei), Changsha (Hunan), Changde (Hunan), Yiyang (Hunan), Guangzhou (Guangdong), Heyuan (Guangdong), Yangjiang (Guangdong), Jieyang (Guangdong), Beihai (Guangxi), Fangchenggang (Guangxi), Yulin (Guangxi), Chengdu (Sichuan), Zigong (Sichuan), Luzhou (Sichuan), Deyang (Sichuan), Mianyang (Sichuan), Suining (Sichuan), Neijiang (Sichuan), Nanchong (Sichuan), Meishan (Sichuan), Yibin (Sichuan), Guangan (Sichuan), Dazhou (Sichuan), Bazhong (Sichuan), Ziyang (Sichuan), Yuxi (Guizhou), Baoshan (Guizhou), Lincang (Guizhou), Xi'an (Shaanxi), Baoji (Shaanxi), Xianyang (Shaanxi), Weinan (Shaanxi), Yan'an (Shaanxi), Hanzhong (Shaanxi), Yulin (Shaanxi), Shangluo (Shaanxi), Jiuquan (Gansu), Qingyang (Gansu)
Cluster 3
Tangshan (Hebei), Qinhuangdao (Hebei), Xingtai (Hebei), Zhangjiakou (Hebei), Chengde (Hebei), Yangquan (Shanxi), Yuncheng (Shanxi), Hegang (Heilongjiang), Daqing (Heilongjiang), Quzhou (Zhejiang), Maanshan (Anhui), Tongling (Anhui), Xinyu (Jiangxi), Zibo (Shandong), Rizhao (Shandong), Zhengzhou (Henan), Luoyang (Henan), Anyang (Henan), Shangqiu (Henan), Huangshi (Hubei), Ezhou (Hubei), Xiangtan (Hunan), Zhangjiajie (Hunan), Huaihua (Hunan), Shaoguan (Guangdong), Shantou (Guangdong), Dongguan (Guangdong), ZhongShan (Guangdong), Guigang (Guangxi), Baise (Guangxi), Hezhou (Guangxi), Laibin (Guangxi), Guangyuan (Sichuan), Leshan (Sichuan), Yaan (Sichuan), Guiyang (Guizhou), Zunyi (Guizhou), Anshun (Guizhou), Lanzhou (Gansu), Zhangye (Gansu), Pingliang (Gansu), Xining (Qinghai), Wuzhong (Ningxia)
Cluster 4
Taiyuan (Shanxi), Datong (Shanxi), Changzhi (Shanxi), Jinzhong (Shanxi), Xinzhou (Shanxi), Linfen (Shanxi), Baotou (Inner Mongolia), Chifeng (Inner Mongolia), Tongliao (Inner Mongolia), Jilin (Jilin), Siping (Jilin), Tonghua (Jilin), Qiqihar (Heilongjiang), Jixi (Heilongjiang), Shuangyashan (Heilongjiang), Yichun (Heilongjiang), Qitaihe (Heilongjiang), Mudanjiang (Heilongjiang), Heihe (Heilongjiang), Suihua (Heilongjiang), Nanjing (Jiangsu), Xuzhou (Jiangsu), Changzhou (Jiangsu), Huaian (Jiangsu), Yangzhou (Jiangsu), Zhenjiang (Jiangsu), Hangzhou (Zhejiang), Ningbo (Zhejiang), Wenzhou (Zhejiang), Jiaxing (Zhejiang), Huzhou (Zhejiang), Shaoxing (Zhejiang), Jinhua (Zhejiang), Taizhou (Zhejiang), Lishui (Zhejiang), Bengbu (Anhui), Huainan (Anhui), Huaibei (Anhui), Anqing (Anhui), Fuyang (Anhui), Suzhou (Anhui), Chaohu (Anhui), Liuan (Anhui), Chizhou (Anhui), Sanming (Fujian), Zhangzhou (Fujian), Nanping (Fujian), Pingxiang (Jiangxi), Jiujiang (Jiangxi), Yingtan (Jiangxi), Ganzhou (Jiangxi), Jian (Jiangxi), Yichun (Jiangxi), Shangrao (Jiangxi), Jining (Shandong), Linyi (Shandong), Binzhou (Shandong), Heze (Shandong), Kaifeng (Henan), Pingdingshan (Henan), Hebi (Henan), Xinxiang (Henan), Puyang (Henan), Sanmenxia (Henan), Nanyang (Henan), Xinyang (Henan), Zhumadian (Henan), Wuhan (Hubei), Shiyan (Hubei), Yichang (Hubei), Jingmen (Hubei), Jingzhou (Hubei), Huanggang (Hubei), Xianning (Hubei), Suizhou (Hubei), Zhuzhou (Hunan), Hengyang (Hunan), Shaoyang (Hunan), Yueyang (Hunan), Chenzhou (Hunan), Yongzhou (Hunan), Loudi (Hunan), Shenzhen (Guangdong), Zhuhai (Guangdong), Foshan (Guangdong), Jiangmen (Guangdong), Zhanjiang (Guangdong), Maoming (Guangdong), Zhaoqing (Guangdong), Huizhou (Guangdong), Shanwei (Guangdong), Qingyuan (Guangdong), Chaozhou (Guangdong), Nanning (Guangxi), Liuzhou (Guangxi), Guilin (Guangxi), Wuzhou (Guangxi), Qinzhou (Guangxi), Hechi (Guangxi), Chongzuo (Guangxi), Haikou (Hainan), Sanya (Hainan), Liupanshui (Guizhou), Kunming (Guizhou), Zhaotong (Guizhou), Lijiang (Guizhou), Puer (Guizhou), Ankang (Shaanxi), Tianshui (Gansu), Wuwei (Gansu), Dingxi (Gansu), Longnan (Gansu), Yinchuan (Ningxia), Guyuan (Ningxia)

to the urbanization trends in China, but the influences of the factor are inferior to those of urban morphology (X_1) and industrial structure (X_2).

The electricity consumption intensity is sensitive to the price of electricity (X_5) in most regions in spite of the fact that the electricity price is regulated and controlled by the government administration. The coefficient of −7.509 on the electricity price (X_5) in component 1 indicates that the enhancement of the electricity price may largely reduce the electricity consumption intensity of the regions in cluster 1. The detailed examination of cluster 1 in Table 5 reveals that most of these cities abound with mineral deposits and rely on resource intensive industry for economic development. This is the evidence of the distortion of electricity price which may induce the discordances of industrial structure such as the overdevelopment of electricity intensive industry.

As the key variable indicated the natural condition the annual average temperature (X_6) affects the utilization of electricity significantly in the region of clusters 2–4. The values of −0.032, −0.062, and −0.186 on ensured reserves of iron ore (X_7) give the detailed description of the cluster probability which is determined by the concomitant variable. It is revealed by the coefficients that the regions in cluster 1 are most related with the endowment in electricity consumption, followed by the regions in cluster 2, cluster 3, and cluster 4 in order. The industrial structure may be the intermediate link which could explain the indirection of the connection between electricity consumption intensity and the resource endowment. These findings show that the industry distribution near the ore sources is one of the characteristics in China and the influence degrees of the determinants of electricity consumption intensity may be varied with the resource endowment.

5. Conclusions and Policy Implications

This study extracts the key factors which determine the electricity consumption intensity of the cities at subprovince and prefecture levels and reveals the acting structure and extent of each determinant which reflects the main characteristics of Chinese social and economic development. The findings of this study are crucial for electricity administration and the specific policies are suggested as follows.

(1) Scrutinizing the underlying influences of potential actions before decision making and formulating the comprehensive policy in consideration of regional characteristics may cause better results. The unitary policy may distort the aims of the policymakers and even upset the initial targets because of the vast spread of development degrees and various effects of different factors.

(2) Optimizing the spatial layout of regional development would improve the efficiency of electricity consumption and decrease the electricity intensity. Since the GPR, population, industry, public finance, and investment are highly concentrated around the core areas of the cities in China, decentralization of regional planning should be taken into account to upgrade the performance of electricity utilization. It is necessary for the government to balance the economic and social development within the regions.

(3) Diversifying the industrial structure, decentralizing economic activities, and establishing multiple cores for regional development would be helpful to achieve lower growth of electricity intensity in China. The integrated consideration of industrial distribution and regional cooperation is needed for the sustainability of economic growth. These immediate actions should be taken especially for the regions in cluster 1 which is most related to the mineral dependent cities.

(4) Besides the regulation powers from the administrative systems, the synthetic system with multiple policy instruments should be established. More attention should be paid to the market oriented mechanism. Also, the price system should be given full scope to adjust the relationship between electricity consumption and economic activities.

(5) Promoting the urbanization in decentralization way and increasing the employment capacities of industry could relieve the pressure on electricity caused by urbanization in China. The influences of the regional concentrating and industry intensifying are greater than that of the urbanization in development. More attention should be paid on the former factors in order to manage the electricity consumption.

(6) Deregulating the electricity price and accelerating the market-oriented reform in energy field could phase down the distortion possibility of energy price system. Extending the industrial chains could lower the electricity consumption in the regions where the development is heavily relied on energy intensive industries. Meanwhile, the unitary energy policy within the country with a vast territory and various degrees of development as China may lead to unrealized results. Energy policies should be synthesized and the multiple factors should be considered adequately before implementation.

Appendix

See Table 5.

Acknowledgments

This study has been supported by the Fundamental Research Funds for the Central Universities, and the Research Funds of Renmin University of China (Grant no. 12XNF017).

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