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Scenario analysis on CO_2 emissions reduction potential in China's electricity sector

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Abstract

With the approach of the year 2012, a new round of international negotiations has energized the entire climate change community. With this, analyses on sector-based emissions reduction and mitigation options will provide the necessary information to form the debate. In order to assess the CO_2 emissions reduction potential of China's electricity sector, this research employs three scenarios based on the "long-range energy alternative planning system" (LEAP) model to simulate the different development paths in this sector. The baseline scenario, the current policy scenario, and the new policy scenario seek to gradually increase the extent of industrial restructuring and technical advancement. Results imply that energy consumption and CO_2 emission in China's electricity sector will rise rapidly in all scenarios until 2030—triple or quadruple the 2000 level; however, through structural adjustment in China's electricity sector, and through implementing technical mitigation measures, various degrees of abatement can be achieved. These reductions range from 85 to 350 million tons CO_2 per year—figures that correspond to different degrees of cost and investment. Demand side management and circulating fluidized bed combustion (CFBC) (ranked in order) are employed prior to use to realize emissions reduction, followed by supercritical plants and the renovation of conventional thermal power plants. In the long term, nuclear and hydropower will play the dominant role in contributing to emissions reduction. It is also suggested that a "self-restraint" reduction commitment should be employed to help contribute to the reduction of emission intensity, an avenue that is more practical for China in light of its current development phase. Setting the year 2000 as the base year, the intensity reduction target could possibly range from 4.2% to 19.4%, dependent on the implementation effectiveness of various mitigation options.

Keywords: Emission reduction; Electricity sector; LEAP model

1. Introduction

With 2012 around the corner, the climate change community has begun to raise concerns on what will happen in the post-Kyoto era, including consideration of what every country's roles and responsibilities will be in the global climate change regime. As the second largest greenhouse gas (GHG) emitter and one of the fastest growing countries in the world, China is facing more and more global pressure to reduce its emissions. China should not waste any more time, but rather immediately focus on building up the capacity for mitigation and adaptation to climate change. This raises a series of crucial questions—How large is China's emission reduction potential? What will be the possible mitigation options to achieve those targets? Will those mitigation options be too expensive for China to carry out?

This study focuses on the emission reduction analysis in China's electricity sector. The reason to choose a sector-based perspective is that it can offer the flexibility to reduce emissions where it is most cost-effective (Bosi and Ellis, 2005) and it may be more feasible and manageable than a country-wide approach (Wang et al., 2007). Many consultants and institutes (Clinton et al., 2005; Schmidt and Helme, 2005; WRI, 2005) have suggested using this perspective. China's electricity sector, characterized by its largest emission of all sectors and fast growth in emission, has naturally become the research focus in this field.

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There has been previous research on CO_2 mitigation in China's electricity sector. The project "Studies on Problems and Solutions in China's Greenhouse Gas Control", funded by GEF and UNDP, was concluded in 1994 by experts from the State Environmental Protection Agency, State Planning Commission, UNDP, World Bank, and various other domestic institutions. The project targeted 14 energy-intensive sectors—including the electricity sector—and provided analysis on the various sector's current energy consumption, future trend, energy efficiency, energy conservation potential, energy conservation technology trend, and those technologies' effects on GHG mitigation. Another project titled "China Climate Change Country Study" was finished in 1996 by the Commission of Science and Technology in China and the US Department of Energy. This project covered 10 sectors—including the electricity sector—and produced techno-economic analysis in those sectors (Research Team of China Climate Change Country Study, 1999). In the research of both Hu and Jiang (2001) and Zhou et al. (2003), several major emission-intensive sectors in China were chosen, which also included the electricity sector. Hu and Jiang (2001) used the assessment integrated model (AIM) and analyzed the current development and future trend of electric technologies. The results of the study recommended adjusting the electricity generation structure, enhancing large-scale electricity generators, and improving end-use efficiency as major ways to achieve CO_2 mitigation. However, Zhou et al.'s (2003) study distinguished itself by the long-range energy alternatives planning (LEAP) system model that it used, while also placing emphasis on technology cost analysis.

As unexpected reforms (described in part II of this paper) have occurred in China's electricity sector during the last 5 years, which is very difficult for those previous studies to foresee, there is an urgent need to re-identify the current situation and future development in this sector in light of the climate change and emissions reduction background. This study is based on a thorough analysis of recent policies and the current situation in China's electricity sector. It employs three scenarios to simulate different development paths. By using the LEAP model, it gives a projection on future electricity sector emission. Different mitigation options are involved in scenario design and the costs for each option have been evaluated. Through scenario comparison, the unilateral climate-friendly actions being done in China in recent years and China's long-term emission reduction potential could be acquired.

2. Background to China's electricity sector

2.1. General situations in China's electricity sector

Hand in hand with the booming economy, China's electric power industry has developed very rapidly over the past 15 years. It is especially the case in the recent 5 years. Total national installed capacity increased from 137.9 Gigawatts (GW) in 1990 to 316.8 GW in 2000, and to 508.41 GW in 2005—the average annual growth rate changed from 8.9% from 1990 to 1999 and to 9.5% from 2000 to 2005. Total power generation rose from 621.3 TWh in 1990 to 2474.7 TWh in 2005—the average annual growth rate changed from 7.8% from 1990 to 1999 and to 12.6% from 2000 to 2005 (See Fig. 1). Despite the fast growth in power generation, electricity supply shortages remain a serious problem in a lot of provinces in China. According to Zhao's (2006) study, in 2002, interruptions in the electricity supply occurred in 12 provincial power grids. In 2003, electricity supply shortages occurred in 23 grids and the supply gap reached 15–20 GW. In 2004, this gap increased to 30 GW.

2.2. Thermal power plants and other power plants in China

China's electricity sector is based on low-cost, plentiful domestic energy resources and low-cost, locally made power generation technologies. Coal has been historically viewed as plentiful and cheap and now supplies the vast majority of electric power stations. In 2005, 75.6% of installed capacity was thermal power and 81.6% of power generation was comprised by thermal generation.

Thermal power plants in China are larger, cleaner, and more efficient than before because all small thermal power plants with unit capacities of less than 50 MW have been required to shut down and any newly produced coal-fired units are required to have capacities of more than 300 MW. We can even see more and more subcritical and supercritical units running in China. Pressurized fluidized bed combustion (PFBC) and integrated gasification-combined cycle (IGCC) systems are also beginning to be utilized in China. They have higher efficiencies and generate fewer emissions than traditional coal-fired power plants, which could help solve the country's energy problems while continuing to utilize the abundance of domestic coal. The problem here is that the systems are also characterized by high costs and technical barriers.

Other than the main coal-fired plants, China has great potential in reducing emissions in other power-generating units. China has the most abundant hydropower resources in the world, with an estimated potential of 380 GW. Aggressive plans have been made to develop hydropower in China. However, hydropower projects have never moved away from arguments of having too great a social, environmental, and ecological cost. China's estimated total natural gas reserves amount to 38 trillion cubic meters (over 1450 Petajoules (PJ)). Proven reserves, however, range from 1.2 to 5.3 trillion cubic meters (roughly 50–200 PJ). China has focused attention—more than ever before—on natural gas power generation projects. China started commercial nuclear power production in 1992 with the 300 MW Qinshan station, and more and more nuclear power stations have been built since. China also has abundant renewable energy resources, including reserves of

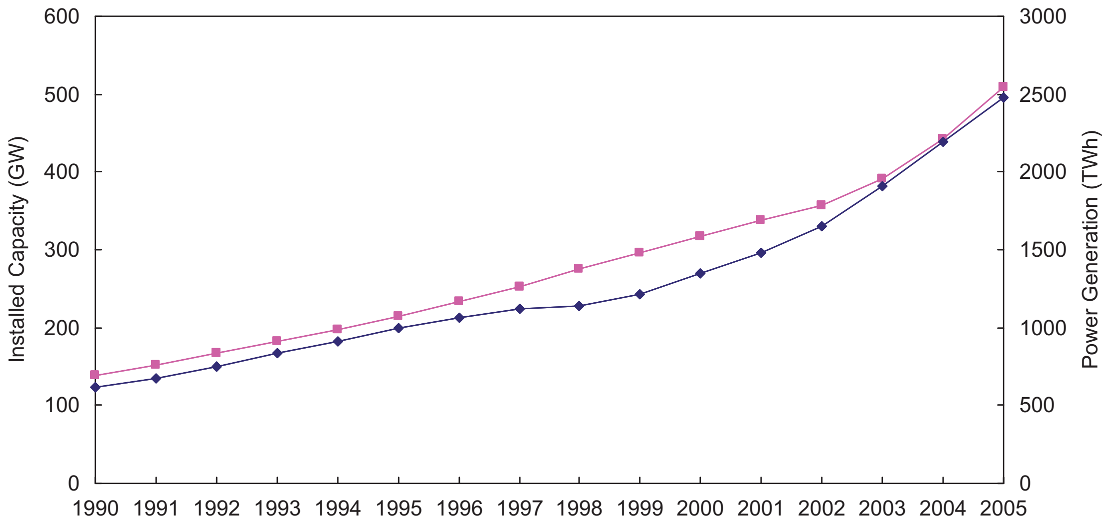

Fig. 1. Development of China's electricity sector. *Source*: China Statistic Bureau (2001–2005).

Table 1
Coal intensity in coal-fired plants in China and in some other industrialized countries (gCE/kWh)

China 2000[a]	China 2005[b]	Germany[c]	Soviet Union[a]	Italy[a]	Japan[d]	France[a]	Canada[a]	UK[a]	US[d]
392	374	310	310	323	330	344	351	356	370

Note: All countries (except China) listed in above are ranked by coal intensity and then alphabetically.
[a]From Zhou et al. (2003), p. 400.
[b]From Zhao (2006).
[c]From Zhou et al. (2003), p. 400. These data are total power plant energy intensity.
[d]From Zhou et al. (2003), p. 400, data in 1995.

253 GW of wind power, and biomass energy resources estimated at an annual supply of 220 million tons of coal-equivalent. Despite the promising resources, these technologies have not been widely adopted mainly because of the high costs, market distortions, and technical barriers.

2.3. Sectoral efficiency

The efficiency of the electricity sector can be evaluated by the coal intensity and emission intensity. Table 1 shows the coal intensity in China and in some other industrialized countries. From this table we can see a big improvement in coal intensity in China from 2000 to 2005, yet there is still a lot of room for improvement. Table 2 shows the average efficiency and the average CO_2 intensity, by fuel, in China's electricity sector in 2000. It can be seen that China still has a lot to improve in the future.

Table 2
Breakout by fuel type electricity sector in 2000

Fuel	Average efficiency (%)	Average CO_2 intensity (kg CO_2/kWh)
Coal	35–45	1.11
Gas	40–58	0.47
Oil	45–50	0.71
Hydro	60–80	–
Nuclear	25–35	–
Wind	10–20	–
Other renewable	5–15	–

2.4. Revolution in China's electricity sector

For the last 50 years, China's electricity sector has gone through numerous phases of change (Zhao, 2006; Xu and Chen, 2006; Yeoh and Rajaraman, 2004; Shiu and Lam, 2004; Andrews-Speed and Dow, 2000; Chandler et al., 1998). After the state monopoly phase (1949–1985), and the gradual market opening phase (1985–1997), China's electricity sector experienced a phase of separation of government functions from corporate functions and testing of generation market competition through provincial pilot programs during 1998–2002. In March 2002, the State Council issued further reforms in the electricity sector and published the Electric Power Reform Plan, which separated the State Power Corporation into the State Grid Corporation of China and China Southern Power Grid Corporation. In addition, they established five generation groups: China Huaneng Group, China Datang Group, China

Huadian Group, China Guodian Group, and China Power Investment Group (China State Council, 2002). In this plan, clean energy is encouraged through pricing in the electricity sector. In 2005, the National Development and Reform Commission also established a series of regulations on electricity pricing. Although the present electricity reform has met some implementation problems, the reform in China's electricity sector still shows a great tendency towards a market-based and competitive electricity system, which means a lower electricity price and more adequately satisfies the country's electricity needs.

All this information would lay the foundation for future projections.

3. Methodology

This study has used an integrated energy-environment and scenario-based accounting model called LEAP, (Stockholm Environment Institute (SEI), 2005) to generate different energy consumption and CO_2 emission scenarios for China's electricity industry. Scenarios are based on comprehensive information of bottom-up electricity-generating technologies, including production ability/percentage of different kinds of power plants, cost/investment of the plants, fuel/energy intensity of the plants, and emission intensity of each fuel/energy. With the powerful accounting ability, LEAP can describe in detail about how energy is consumed, converted, and produced in a given region or economy under a range of alternative assumptions on population, economic development, technology, price, and so on. Furthermore, through comparing the results driven by different scenarios, the energy-saving potential and the CO_2 abatement potential under different scenarios in any target year or during the whole target period can be acquired.

The analytical procedure in the LEAP model is described in Fig. 2. Content in the frame of broken lines should be illuminated both in baseline and abatement scenario. The procedure can be summarized as five steps: sectoral production projection, corresponding energy demand, CO_2 emissions, total cost calculation, and energy savings and CO_2 abatement potential calculation.

3.1. Step 1: sectoral production

The production output of the electricity industry will be described in terms of the production output from each fuel type, such as coal, oil, and natural gas:

$$P_i = \sum_j p_{j,i}, \tag{1}$$

where P_i is the production output of fuel i, $p_{j,i}$ is the production output by fuel i through equipment j. During the construction of the model, we assume that output of electricity production is the same among all scenarios and is exogenous to the model, in order to avoid uncertainty when forecasting production and help researchers focus on analyzing the differences between scenarios, which is mainly due to industrial restructuring and technological advancement (Wang et al., 2007). Once total sector production is given, according to the different equipment composition assumptions in different scenarios, $p_{j,i}$ (production output from each equipment) is acquired.

3.2. Step 2: energy demand from electricity sector

$$E = \sum_i \sum_j e_{j,i} p_{j,i}, \tag{2}$$

where E is the total energy demand of the electricity industry, $e_{j,i}$ is the unit production energy consumption of fuel type i used in equipment j. $e_{j,i}$ is cited from statistics and previous research and is shared among scenarios. Different equipment compositions in scenarios will result in various $p_{j,i}$ and therefore reflect on the changes on energy demand.

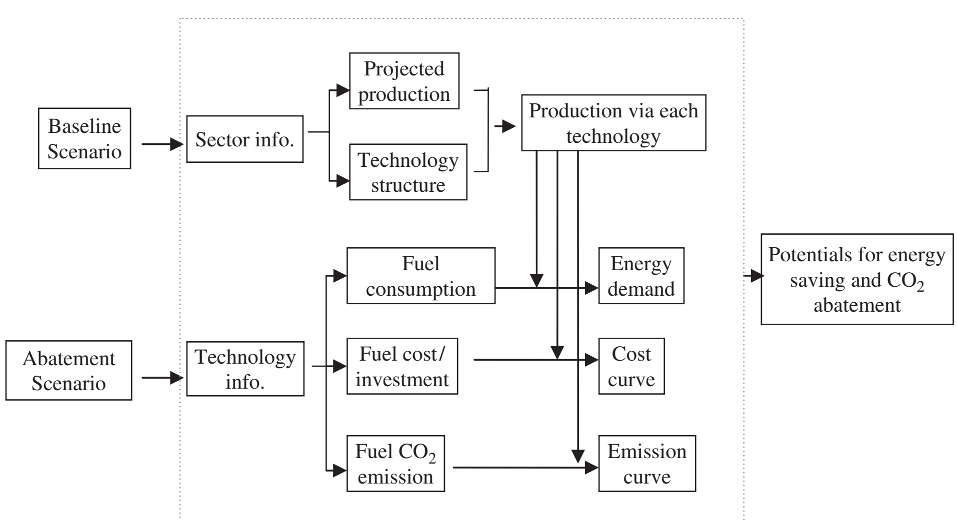

Fig. 2. Structure and analytical procedure of LEAP model.

3.3. Step 3: CO_2 emission from electricity sector

$$CE = \sum_i \sum_j cef_{j,i} e_{j,i} p_{j,i}, \tag{3}$$

where CE is the total CO_2 emission of the electricity industry, $cef_{j,i}$ is the CO_2 emission factor from fuel type i through equipment j. $cef_{j,i}$ is also cited from statistics (including LEAP technical database) and previous research and is shared among scenarios. Different scenarios will differ in their CO_2 emissions.

3.4. Step 4: costs in electricity sector

$$C = \sum_i \sum_j \left\{ \left[\sum_i (e_{j,i} ep_i) + \sum_k (m_{k,j} mp_k) + fc_j \right] p_{j,i} \right\}, \tag{4}$$

where C is the total cost of the electricity industry including equipment fixed costs and variable costs for raw materials and fuels, ep_i is the unit price of fuel type i, $m_{k,j}$ is the demand for raw material k per unit of production used in equipment j, mp_k is the unit price of raw material k, and fc_j is the fixed cost per unit production through equipment j. $p_{j,i}$ will be affected due to a larger penetration of more advanced and costly equipments for instance. Although the fixed costs and variable cost per unit of production from this equipment remain, the costs in electricity sector will change.

3.5. Step 5: energy savings and CO_2 abatement potentials in the electricity sector

As stated earlier, the energy savings and CO_2 abatement potentials could be obtained through scenario comparison.

3.6. Summary

In the emission reduction analysis in China's electricity sector, a scenario analysis method based on the LEAP model has been selected. Each scenario represents a different development path, which is possible in China's electricity sector due to various policies. A common projection for future power generation is assumed to be shared among these scenarios. Scenarios will be based on previous policies and projected policy direction, and will differ in their technical compositions in generating electricity. This could result in changes in energy demand, CO_2 emission, and sectoral production costs. By comparing these scenarios, the energy-saving and CO_2 abatement potential in China's electricity sector can be acquired.

4. Scenario design

4.1. Scenario description

A baseline scenario (scenario 1), a current policy scenario (scenario 2) and a new policy scenario (scenario 3) have been generated in the model. Differences among the three scenarios are listed in Table 3. Scenario 1 only takes into account industry polices adopted before 2000, and scenario 2 takes into account policies adopted between 2000 and 2005. Scenario 3, which is also called the mitigation scenario, assumes the adoption of more ambitious energy conservation and emissions reduction measures.

The time span for this scenario analysis is from 2000 to 2030, with the year 2000 as the baseline year.

It should be noted that carbon capture and storage (CCS) is suitable for use in all kinds of coal-fired technologies. However, this technology is still in its research and development phase and will need some time to reach a point where it is suitable for commercial use. Here we simply make assumptions on the emissions reduction effects of CCS in scenario 3, after collating information from related studies (Xu, 2006; Senior, 2006; Georgia, 2005; Simbeck, 2004).

4.2. Main assumptions and sources in scenario definition

The technology composition is the same in 2000 among the three scenarios. The development policies in Section 2.4 form the driving forces for the gradual differences in technology composition in the following years, from 2000 to 2030 (see Appendix for detailed information). Table 3 describes in detail about the policies and regulations, which give out goals and directions for each technology or equipment to develop. Scenario 1 changes the technical composition only according to policies before 2000 and the natural technical improvement. Scenario 2 differs in the technical composition because it refers to recent policies, especially several explicit targets to reach implied targets in these policies (such as the percentage of nuclear power in the total electricity generation in a certain year). Technical composition in scenario 3 is based on scenario 2 and the study on the advanced climate-friendly technologies. It allows for the larger penetration of these technologies. In all scenarios, coal remains to act as the primary energy source for electricity generation in China. High-efficiency large-scale plants and those that employ clean and renewable energies will account for a greater share of the generation output under the more aggressive scenarios.

In all scenarios, there are some general assumptions. We assume that the exchange rate of the US dollar to the Chinese RMB is 1 USD to 8.2784 RMB. The assumption is also that the discount rate is defined to be 10%.

4.3. Production output projection for China's electricity sector

The sector's production output forecast is the first stage of the entire analysis process. Here we refer to the Report of the Sixteenth National Congress of the CPC and assume that China's GDP in 2020 will be quadruple the figure of 2000. Even with a number of previous studies on China's electricity production (Yang and Yu, 2004; Shiu and Lam,

Table 3
Scenarios analyzed in this study

Scenarios	Policies and measures	Scenario description
Scenario 1: baseline scenario	It remains the tendency until year 2000, which does not take mid- and long-term plans and industrial development plans occurring afterwards into consideration	Of the three scenarios, this is the most conservative in projecting technical development in the electricity sector. The main options are focused on demand-side management; improving energy efficiency of end-users; SO_2 and NO_x control; and reforms in old coal-fired plants. Generation ratio by renewable energy grows slowly
Scenario 2: current policy scenario	Planning and policies until 2005 have been emphasized, such as The Report of The Sixteenth National Congress of the CPC, sectoral planning in the 10th five-year plan, and mid- and long-term development plans	Installed capacities of current power plants have been enlarged and small-scale equipments have been phased out of the market. The technology level is higher than in scenario 1. Advanced generation technologies have been widely introduced, such as PFBC and IGCC. The massive Three Gorges Dam will go into service from 2009 and the installed capacity will reach 18.2 MW. Nuclear installed capacity will reach 40 MW, about 4% of the national installed capacity. The Renewable Energy Law published in 2005 will give renewable energy power plants effective financial and technical support
Scenario 3: new policy scenario	Pressure from achieving energy-conservation and emissions reduction has prompted the implementation of stricter policies and sectoral regulation	All plants less than 50 kW have to be closed before 2003 and all plants less than 100 kW have to be gradually phased out of the market. Supercritical turbine generators will be used in projects from 2015. Carbon capture and storage (CCS) starts service in 2020, and can mitigate 60 million tons of CO_2 nation-wide until 2030. Other advanced coal-fired technologies will be used to a larger extent than in scenario 2. Clean energy power plants such as hydro, nuclear, wind, and solar will have a bigger generation ratio.

2004; Hirschhausen and Andres, 2000), it is still difficult to make projections due to the rapid on-going rate of development. Here we make a simple assumption that electricity production growth will be consistent with economic development, as shown in Table 4. The forecast for electricity generation is shown in Fig. 3.

5. Scenario analysis results

5.1. Energy consumption

In all scenarios, energy consumption maintains a consistent upward growth pattern, though there are differences in the growth rate. An increase in electricity production is the main driving force for this. This overshadows even emissions reduction from equipment replacement and improvements in technology. This trend is shown in Fig. 4. Energy consumption in scenario 1 increases from 325 million tons of oil equivalents in 2000 to 1419 million tons of oil equivalents in 2030. In scenarios 2 and 3, the projected energy consumption in 2030 is 1369 and 1162 million tons of oil equivalents, while realizing the energy conservation of 50 and 257 million tons, respectively. It is worthy to note that the energy conservation realized in 2030 in the new policy scenario is very impressive by its closeness to the total energy consumption in 2000 in the electricity sector.

5.2. CO_2 emission and emission reduction potential

Table 5 displays CO_2 emissions from different scenarios. 2000 is the base year. Scenario 1 represents the most conservative CO_2 emissions projection. It shows that if no controls were made in China, from 2000 to 2030, there is likely to be 134 million tons more CO_2 emitting from China's electricity sector every year.

Scenario 2, which considers the current national and sectoral polices, can achieve emission reduction of 143 MMT in 2020 and 193 MMT in 2030. The cumulative CO_2 emission reduction between scenarios 1 and 2—from 2000 to 2030—is 2558 million tons, about 85 million tons abatement per year. The cumulative emission reduction achieved by scenario 2 is more than two times of the 2000 emission in China's electricity sector. This shows the unilateral and voluntary actions taken by China, which contribute to GHG mitigation and climate change through current policies.

Scenario 3, characterized by its aggressive GHG control policies, can achieve emission reduction of 426 MMT in 2020 and 993 MMT in 2030. An average 350 million tons of CO_2 is reduced every year compared with the baseline

Table 4
China's GDP and electric production assumptions in the analysis

Year	2000	2005	2010	2015	2020	2025	2030
Annual growth rate (%)		7.50		6.50		5.50	
GDP (billion US$)	1081	1552	2227	3096	4181	5465	7142
Sectoral production (TWh)	1369	1841	2313	3179	4046	5664	7282

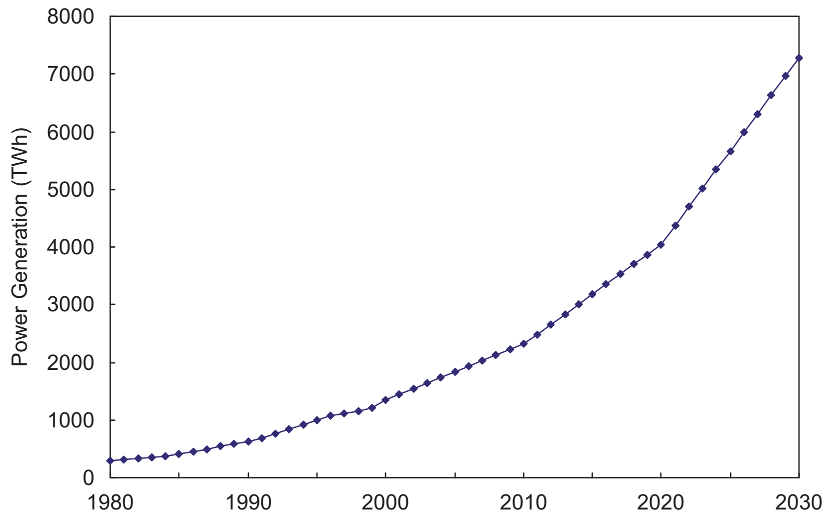

Fig. 3. Historical electricity generation and forecast.

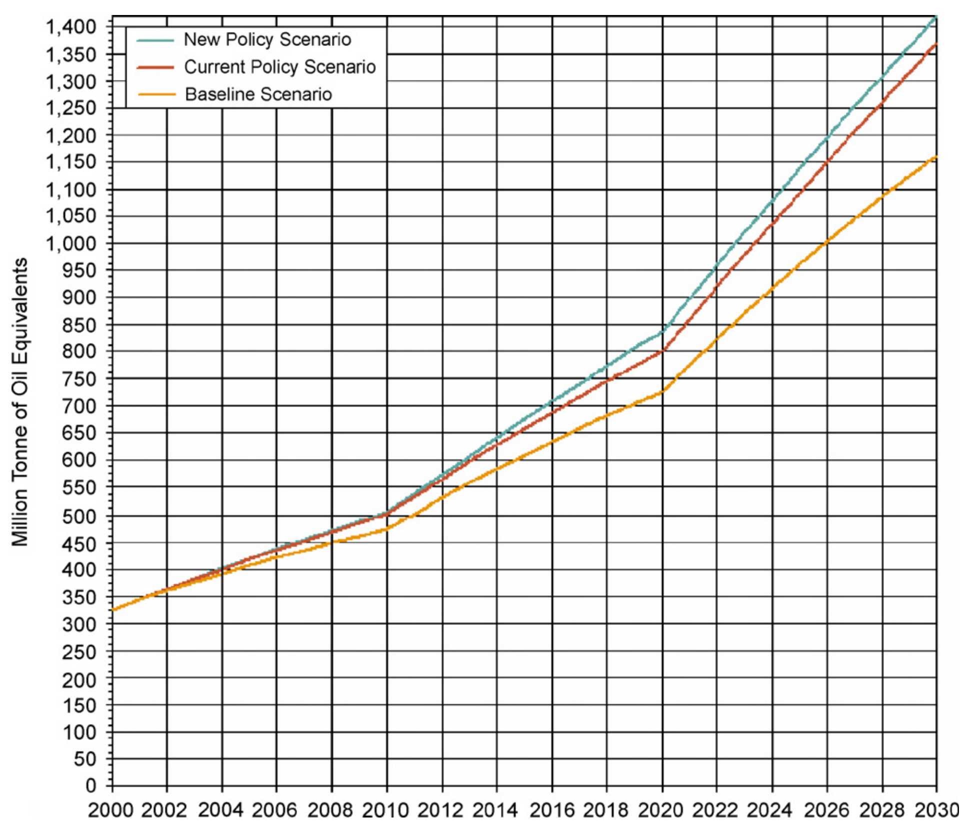

Fig. 4. Energy consumption forecast for different scenarios, 2000–2030.

Table 5
CO_2 emissions of different scenarios (MMT)

Year	2000	2010	2020	2030
Scenario 1	1199	1877	3102	5231
Scenario 2	1199	1865	2959	5038
Scenario 3	1199	1760	2676	4238

scenario. Cumulative emission reduction from 2000 to 2030 in scenario 3 compared with scenario 1 could reach 10,486 MMT, nearly 10 times of the 2000 emission. These emission reduction potentials are mainly acquired from more ambitious energy conservation and GHG control measures, in the form of industrial restructuring and technological advancement.

5.3. Energy intensity and CO_2 intensity

Table 6 lists quantitative results for energy and CO_2 emissions. As the development process continues, each scenario will experience decreasing energy intensity and CO_2 intensity. This is because energy-saving practices and environmental protection awareness have influenced each sector's development plans, rendering these measures as basic principles that all observe. However, when we compare amongst the three scenarios, an obvious trend emerges, namely that more aggressive scenarios have lower energy and CO_2 intensity. From both the energy and CO_2 intensity perspectives, in 2030, scenario 2 can realize, respectively, a 3.6% and 4.2% reduction compared with scenario 1, and scenario 3 can affect an even greater reduction at 18.1% and 19.4%, respectively.

5.4. Cost and mitigation options evaluation

It is crucial to discuss cost while considering mitigation analysis. A very effective mitigation scenario may fail to be utilized due to its unacceptably high cost of implementation. Another reason that cost is important is that information on cost can help a lot when deciding the preference and utilization orders of mitigation options, which in turn make the mitigation plan a much more detailed one. Besides, cost may change with changes in the development process. Some technologies or mitigation options' cost may rise due to the increasing difficulties in implementation, which will result in the technology or option being phased out. Some other costs may decrease due to technical improvements, which will give the said technology or option a bigger opportunity to impact the sector.

Tables 7–9 lists abatement potentials and corresponding cost information of the possible mitigation options under scenario 3 compared with scenario 1 in 2010, 2015, and 2020. The parallel data after 2020 have not been analyzed due to the high uncertainty on technology development and cost information. These mitigation options are ranked in accordance with their cost effectiveness, also called marginal abatement cost. Negative cost effectiveness means that the mitigation option will achieve emissions reduction; meanwhile, the long-term gains from energy conservation will surpass the initial investment, which results in net benefits (negative cost). The total cost to realize scenario 3 in 2020 would reach US$10.89 billion, US$24.3 for each ton of CO_2 reduced.

In these tables, mitigation options with a lower cost are applied first, then those options with a higher cost. The inclusion of new options will result in rising cumulative emissions reduction, but will also result in an increase in total cost, in the growth rate of the total cost, and in the average abatement cost of all options.

"Soft" measures such as demand-side management in the electricity sector is of higher priority in the early years of the scenario analysis period. But such measures only account for a small proportion of overall emissions reduction. Along with industry development—although the cost of this kind of measure will be lower—the emissions reduction potential will fall, which makes cost-effectiveness decline. CFBC will also be suggested prior to use due to its negative cost and impressive mitigation effects. Although having positive costs, the creation of supercritical plants and the reconstruction of conventional thermal power plants are still priorities to be acted upon in the near future. This is because the costs of implementation remain at a low level, and their usage utilizes China's vast and abundant coal reserves. Conversely, there is a huge cost increase resultant from the implementation of clean energy technologies, such as nuclear power and hydropower. They are characterized by comparatively high costs but—from a long-term perspective—they can play a fundamental role in China's emissions reduction process. Other mitigation options such as natural gas, wind power, IGCC and PFBC, CCS, and solar thermal are options that China might revisit after 2030 because the implementation of those technologies is extremely costly, and their abatement potential can hardly compare to the aforementioned options. This information is also displayed in Fig. 5, where we see that the average cumulative abatement cost increases, first mildly and then aggressively. It implies that most part of the reduction could be realized by those relatively low-cost options (less than US$50/ton CO_2). However, if more reduction needs to be achieved, the following options will cost so much more but the mitigation effects still cannot be satisfactory.

Table 6
Energy and CO_2 intensity in China's electricity sector

Year	Scenario 1		Scenario 2		Scenario 3	
	Energy intensity (PJ/TWh)	CO_2 intensity (MMT CO_2/kWh)	Energy intensity (PJ/TWh)	CO_2 intensity (MMT CO_2/kWh)	Energy intensity (PJ/TWh)	CO_2 intensity (MMT CO_2/kWh)
2000	9.94	0.88	9.94	0.88	9.94	0.88
2005	9.53	0.85	9.50	0.85	9.25	0.83
2010	9.13	0.81	9.07	0.81	8.57	0.76
2015	8.89	0.79	8.67	0.77	8.04	0.71
2020	8.66	0.77	8.28	0.73	7.52	0.66
2025	8.41	0.74	8.08	0.71	7.10	0.62
2030	8.16	0.72	7.87	0.69	6.68	0.58

Table 7
Abatement potential and corresponding cost information of mitigation options under scenario 3 compared with scenario 1 in 2010

No.	Mitigation options	Marginal mitigation cost (US$/ton CO_2)	Total emission reduction (MMT CO_2)	Total cost (million US$)	Cumulative emission reduction (MMT CO_2e)	Cumulative net cost (million US$)	Average cumulative cost effectiveness (US$/MMT CO_2e)
1	Demand-side management	−9.86	7.59	−74.8	7.59	−74.8	−9.86
2	CFBC	−4.55	1.21	−5.52	8.80	−80.3	−9.13
3	Reconstruction of conventional thermal power	6.59	10.3	68.1	19.1	−12.3	−0.64
4	Supercritical plant	12.5	6.58	82.0	25.7	69.7	2.71
5	Nuclear power	34.2	31.1	1063	56.8	1133	20.0
6	Hydropower	46.0	54.9	2526	111.7	3659	32.8
7	Natural gas	50.8	1.11	56.6	112.8	3715	32.9
8	IGCC and PFBC	66.4	3.54	235.1	116.4	3950	33.9
9	Wind power	80.8	1.32	106.3	117.7	4057	34.5
10	Solar thermal	229.3	1.52	348.1	119.2	4405	37.0

Table 8
Abatement potential and corresponding cost information of mitigation options under scenario 3 compared with scenario 1 in 2015

No.	Mitigation options	Marginal mitigation cost (US$/ton CO_2)	Total emission reduction (MMT CO_2)	Total cost (million US$)	Cumulative emission reduction (MMT CO_2e)	Cumulative net cost (million US$)	Average cumulative cost effectiveness (US$/MMT CO_2e)
1	Demand-side management	−5.28	17.0	−89.7	17.0	−89.7	−5.28
2	CFBC	−4.04	2.62	−10.6	19.6	−100.3	−5.11
3	Reconstruction of conventional thermal power	6.67	22.2	148.3	41.9	48.0	1.15
4	Supercritical plant	8.3	14.4	119.6	56.3	167.6	2.98
5	Nuclear power	26.0	69.8	1816	126.0	1984	15.7
6	Hydropower	38.6	113.4	4373	239.4	6356	26.6
7	Natural gas	40.3	2.40	96.7	241.8	6453	26.7
8	IGCC and PFBC	50.5	8.1	408	249.9	6861	27.5
9	Wind power	53.0	3.1	161.8	252.9	7022	27.8
10	Solar thermal	171.3	3.5	598	256.4	7620	29.7

Table 9
Abatement potential and corresponding cost information of mitigation options under scenario 3 compared with scenario 1 in 2020

No.	Mitigation options	Marginal mitigation cost (US$/t$CO_2$)	Total emission reduction (MMt CO_2)	Total cost (million US$)	Cumulative emission reduction (MMT CO_2e)	Cumulative net cost (million US$)	Average cumulative cost effectiveness (US$/MMT CO_2e)
1	CFBC	−3.63	5.71	−20.7	5.71	−20.7	−3.63
2	Demand-side Management	−2.96	38.0	−112.6	43.7	−133.3	−3.05
3	Supercritical plant	5.72	25.1	143.6	68.8	10.3	0.15
4	Reconstruction of conventional thermal power	5.99	29.7	177.7	98.5	188.0	1.91
5	Nuclear power	19.2	136.9	2629	235.5	2817	12.0
6	Hydropower	31.0	171.2	5306	406.6	8123	20.0
7	Natural gas	32.7	4.18	136.8	410.8	8260	20.1
8	Wind power	38.0	7.61	289.1	418.4	8549	20.4
9	IGCC and PFBC	38.8	14.1	546.1	432.5	9095	21.0
10	IGCC–CCS	53.3	5.00	266.5	437.5	9362	21.4
11	Solar thermal	133.7	11.4	1526	448.9	10888	24.3

6. Conclusion

Energy consumption and CO_2 emissions from China's electricity sector are projected in this paper through the employment of three different scenarios based on the LEAP model. China's electricity sector will develop rapidly until 2030, along with the booming economy and the high electricity demand from industry and society.

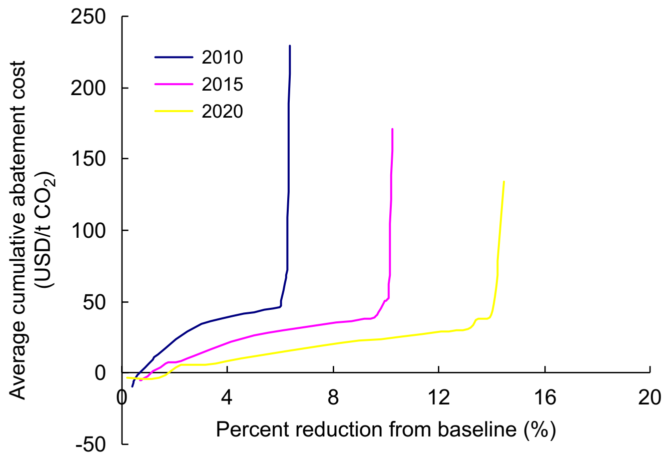

Fig. 5. Average cumulative abatement cost for different percent reductions from the baseline scenario.

Correspondingly, the CO_2 emissions under the baseline scenario will rise significantly. Through structural adjustment in China's electricity sector—and through the implementation of several technical measures—various degrees of abatement can be achieved. However, the level of abatement potential that can be achieved will be limited by the technical abatement potential and corresponding costs.

During 2000–2005, the period of China's 10th five-year plan (based on existing policies, measures, and standards), China established and implemented various new policies with ambitious objectives on sustainable development and industrial restructuring in the electricity sector. The current policy scenario (scenario 2) represents all the new tendencies and displays a cumulative CO_2 abatement potential of 2558 million tons from 2000 to 2030, about 85 million tons abatement per year. In scenario 2, energy intensity and CO_2 intensity will also decline by 3.6% and 4.2%, respectively, until 2030, compared with the baseline scenario. In a sense, scenario 2 exemplifies the voluntary adherence of China's recent policies to GHG emissions reduction.

But as we approach the post-Kyoto era, the implementation of current policies can barely fulfill the growing needs for climate change mitigation options. From the analysis of the new policy scenario (scenario 3), we find out that there is a huge emissions reduction potential in China's electricity sector, when all mitigation options are assumed to have good implementation results. The average CO_2 abatement per year in the new policy scenario compared with the baseline scenario is 350 million tons, which is 265 million tons less emissions than under the current policy scenario.

Cost information has to be considered when trying to implement mitigation options. The total cost estimated to realize scenario 3 in 2020 would reach US\$10.89 billion, and the average cumulative cost for each ton of CO_2 emissions reduction would reach US\$24.3. The average cumulative emission reduction cost rises when more mitigation options are used. When assessing each possible technical measure, and then formulating feasible abatement plans, it is absolutely necessary to utilize the criteria of corresponding costs. Of course, those measures with a lower cost and a relatively high abatement potential will have higher priority. In the short term, demand-side management and CFBC will be suggested to be utilized first due to their negative cost and quick results in emissions reduction. The second best mitigation options to be acted upon in the future are the creation of supercritical plants and the reconstruction of conventional thermal power plants. Nuclear power and hydropower, though with comparatively high costs, can play fundamental roles in emission reduction in the long run. Mitigation options like natural gas, wind power, IGCC and PFBC, CCS, and solar thermal are so costly and ineffective that they might become attractive after 2030.

Based on this research, it will be interesting to give a short comment on China's reduction commitment, there is no doubt that China's electricity sector will maintain its tendency of fast growth until the 2030s, and, accordingly, emissions will also continue to increase. Sectoral production and emission intensity are two main factors that influence sectoral emissions. China's economy is widely believed to maintain its rapid growth rate. Therefore, as a fundamental part of economic development (and in people's daily lives), the electricity sector in China cannot accept an absolute emissions cap. What seems more practical is a sectoral relative emissions reduction target or, in other words, a target for emission intensity. But China's coal-based energy structure determines that China's electricity sector will face great difficulties in meeting international emission intensity standards. Therefore, a more realistic consideration is the development of a "self-restraint" reduction commitment to achieve a definite decline in the proportion of emission intensity. According to the results of the scenario analyses (with 2000 as the base year), the target for intensity decline will possibly range from 4.2% to 19.4%, a range corresponding to the extent of the implementation of mitigation options.

The "self-restraint" reduction commitment needs to be combined with China's national sustainable development strategy and the electricity sector's objectives on structural adjustment and technical improvement. In fact, even under the scenario of having no emissions reduction obligations, China's electricity sector can still seek for a "win-win" situation for both technical progress and emissions reduction through participation in international abatement efforts. In international negotiations on the climate change regime (especially for the sectoral approach), emissions reduction targets are important, and specific financial and technology transfer mechanisms are also significant to ensuring the successful achievement of emissions reduction.

Table A1

	Scenario 1				Scenario 2				Scenario 3			
	2000	2010	2020	2030	2000	2010	2020	2030	2000	2010	2020	2030
Thermal power plants												
<50 MW	12.6	0.0	0.0	0.0	12.6	0.0	0.0	0.0	12.6	0.0	0.0	0.0
50–100 MW	6.9	6.4	5.5	4.0	6.9	6.0	5.0	3.0	6.9	5.4	4.0	2.0
100–300 MW	52.4	48.3	36.6	23.7	52.4	47.4	31.5	19.2	52.4	43.3	23.9	6.9
Subcritical units	3.0	5.0	7.0	10.5	3.0	5.5	8.0	12.5	3.0	5.8	8.3	12.6
SC/USC units	0.0	8.5	12.3	15.7	0.0	9.1	13.4	16.2	0.0	9.5	14.5	17.2
CFBC	1.0	3.5	7.8	12.3	1.0	3.7	8.5	13.3	1.0	3.9	9.4	15.6
IGCC	0.0	0.3	0.9	1.9	0.0	0.3	1.0	2.0	0.0	0.3	1.5	2.4
PFBC	0.0	0.3	0.8	1.4	0.0	0.3	1.0	1.6	0.0	0.3	1.4	2.3
Oil-fired	3.0	2.3	1.2	0.1	3.0	1.9	1.1	0.1	3.0	1.8	0.9	0.1
Natural gas	2.0	2.9	3.3	3.8	2.0	2.9	3.3	3.8	2.0	2.9	3.3	3.8
CCS mitigation ($MtCO_2$)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0
Hydropower	17.8	19.3	20.1	20.2	17.8	19.3	21.0	21.3	17.8	21.5	22.8	24.8
Nuclear	1.2	2.6	3.4	5.1	1.2	2.9	5.0	5.6	1.2	4.5	8.5	10.6
Wind power	0.0	0.5	1.0	1.2	0.0	0.6	1.1	1.3	0.0	0.7	1.4	1.6
Other renewables	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	100	100	100	100	100	100	100	100	100	100	100	100

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Appendix. Main technical structure change under different scenarios (%)

See Table A1.

References

Andrews-Speed, P., Dow, S., 2000. Reform of China's electric power industry. Challenges facing the government. Energy Policy 28, 335–347.

Bosi, M., Ellis, J., 2005. Exploring Options for Sectoral Crediting Mechanisms. OECD/IEA.

Chandler, W., et al., 1998. China's Electric Power Options: An Analysis of Economic and Environmental Costs. Battelle Memorial Institute, Washington, DC, USA.

China State Council, 2002. Notice on Revolution of Electricity Sector Management. Online at: 〈http://www.china5e.com/laws/index2.htm?id=200608080001〉 (in Chinese).

China Statistic Bureau, 2001–2005. Electricity Statistic Yearbook 2001, 2002, 2003, 2004, 2005. China Statistics Press, Beijing, China (in Chinese).

Clinton, W., John, N., Rt. Hon. Simon, U., Petra, H., 2005. Can transnational sectoral agreements help reduce greenhouse gas emissions? Background paper for the meeting of the Round Table on Sustainable Development, World Bank. OECD, 1–2 June 2005.

Georgia, P., 2005. Potential of CO_2 capture and geological storage in the world. Presentation in Les Cahiers du CLIP n17, IDDRI, Paris.

Hirschhausen, C., Andres, M., 2000. Long-term electricity demand in China – From quantitative to qualitative growth? Energy Policy 28, 231–241.

Hu, X., Jiang, K., 2001. Evaluation of Technology and Countermeasure for Greenhouse Gas Mitigation in China. China Environmental Science Press, Beijing, China (in Chinese).

Research Team of China Climate Change Country Study, 1999. China Climate Change Country Study. Tsinghua University Press, Beijing (in Chinese).

Schmidt, J., Helme, N., 2005. Operational issues for a sector-based approach: questions and answers. Working paper prepared for CCAP's Dialogue on Future International Actions to Address Global Climate Change.

Senior, B., 2006. Addressing the challenge of coal use in China through carbon capture and storage. Presentation to Italy–UK Clean Coal/CCS Workshop.

Shiu, A., Lam, P., 2004. Electricity consumption and economic growth in China. Energy Policy 32, 47–54.

Simbeck, D., 2004. CO_2 capture economics. Workshop Proceedings from The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, The Pew Center.

Stockholm Environment Institute (SEI), Tellus Institute, 2005. LEAP: Long Range Energy lternatives Planning System, User Guide for LEAP 2005. Online at: 〈http://forums.seib.org/leap/documents/Leap2005UserGuideEnglish.pdf,2005S〉.

Wang, K., Wang, C., Lu, X., Chen, J., 2007. Scenario analysis on CO_2 emissions reduction potential in China's iron and steel industry. Energy Policy 35, 2320–2335.

WRI, 2005. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy.

Xu, J., 2006. Finding the way out for emission reduction in China. Scientific Times. June 1. Online at: ⟨http://www.china5e.com/dissertation/criterion/20060807150248.html⟩ (in Chinese).

Xu, S., Chen, W., 2006. The reform of electricity power sector in the PR of China. Energy Policy 34, 2455–2465.

Yang, M., Yu, X., 2004. China's rural electricity market—a quantitative analysis. Energy 29, 961–977.

Yeoh, B.S., Rajaraman, R., 2004. Electricity in China: the latest reforms. The Electricity Journal, 61–69.

Zhao, Y., 2006. Current status of electric power sector in China. Presentation on March 26 Beijing Project Workshop.

Zhou, D., Dai, Y., Yu, C., et al., 2003. China's Sustainable Energy Scenarios in 2020. China Environmental Science Press, Beijing, China (in Chinese).