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Carbon charges and natural gas use in China

Jeffrey Skeer[a,*], Yanjia Wang[b]

[a]Asia Pacific Energy Research Centre (APERC), 1-13-1 Kachidoki, Chuo-ku, Tokyo 104-0054, Japan
[b]APERC and Tsinghua University, Beijing 100084, China

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Abstract

Substitution of natural gas for coal in China's power sector could significantly reduce emissions of carbon dioxide, but gas-fired power is generally more costly than coal-fired power in China today. This paper explores how carbon charges and carbon sequestration technology might tip the balance in favour of gas. The costs of electricity from new coal-fired and gas-fired power plants in China are compared under various assumptions about fuel costs, exchange rates, carbon dioxide charges, and application of carbon sequestration technology. Under average cost conditions today, gas-fired power is roughly two-thirds more costly than coal-fired power. But with a charge of $20/tonne of carbon dioxide, the costs of gas- and coal-fired power would typically be about equal. Over the longer term, carbon sequestration technology could be economical with a carbon dioxide charge of $22/tonne or more under typical cost conditions, but gas with sequestration would not have a clear cost advantage over coal with sequestration unless the charge exceeded $35/tonne.

Keywords: China; Carbon dioxide; Natural gas

1. Introduction

Coal is used to generate about three-quarters of China's electricity (Table 1) and is likely to remain the dominant fuel for electric power production in the foreseeable future (CERS, 2002; SETC, 2003; Zhang et al., 2002). Yet natural gas is starting to be promoted by Chinese authorities due to its relatively low emissions of atmospheric pollutants and carbon dioxide. Thus it is interesting to examine the extent to which natural gas might be a realistic alternative to coal for electricity generation. At what level would carbon taxes tip the economic calculus in favour of gas-fired power? Could carbon sequestration technology preserve a key role for coal in China's power mix as concerns mount over global warming, limiting pressure on gas markets?

Under current conditions, coal-fired power is usually much cheaper than gas-fired power in China since domestic coal is so abundant. Indeed the fuel cost disadvantage of gas is likely to widen over the years as growing demand for gas around the world puts pressure on limited gas supplies. But due to concerns over the public health impacts of poor air quality in major cities, China is imposing charges on emissions of atmospheric pollutants, and such charges may increase over time. The government has persisted in building the West-to-East gas pipeline, as well as new gas-fired power plants to use the pipeline's gas, even though the delivered gas is very costly. In addition, as concerns grow over global warming, a market value may be attached to carbon emissions. Hence, environmental factors could tilt the economic balance in favour of less polluting natural gas, while hastening development of China's abundant hydro and wind power resources.

2. Future directions in China's generating mix

While projections of China's future generating mix differ, most analysts agree on several scores:

*Corresponding author. Tel.: +1 202 5863662; fax: +1 202 5860013.
E-mail address: jeff.skeer@hq.doe.gov (J. Skeer).

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Table 1
Fuel shares of generating capacity and output in China in 2002

Powerplant type	Electric generating capacity		Electricity generated	
	Amount (GW)	Share (%)	Amount (TWh)	Share (%)
Coal-fired	252.1	66.5	1281	74.4
Gas- or oil-fired	12.1	3.2	61	3.6
Large hydropower	84.6	22.3	271	15.7
Other renewable	26.0	6.9	83	4.8
Nuclear power	3.7	1.0	25	1.5
Total	378.5	100.0	1721	100.0

Sources: (SETC, 2003; CERS, 2002; Zhang et al., 2002).

- Coal will continue to dominate the generating mix for decades to come. Domestic coal is cheap and abundant, so other fuels cannot easily compete (IEA, 2002).
- Gas-fired power plants should play a small but growing role in the generating mix over time, despite relatively high costs, because of their superior environmental performance, short construction time and flexibility to follow loads up and down.
- Oil use for power generation will remain marginal due to policies to limit such use.
- Hydropower is expected to provide a fifth to a quarter of China's generating capacity through 2020, steadily expanding with completion of the gigantic Three Gorges project and seven other large-scale plants. But expansion of hydropower will be limited by high construction costs, long construction periods, the site-specific nature of each plant, and impacts on the riverine environment (SETC, 2002).
- Renewable energy sources other than hydro will play but a modest role in China's power mix before 2020. But China has large wind resources, within reasonable distances of major cities, that could well be developed in the foreseeable future.
- Nuclear power plants will play a growing but modest role, despite their capital intensity and long construction times, due to their inclusion in national plans. By 2020, 28 new plants are to be added to 9 in service, so that nuclear capacity expands from 7 to 32 GW, coming to generate 4% of the economy's electricity. (Zhou et al., 2003; Li, 2003).

Yet despite the continued dominance of coal in the electric power sector, several recent developments should promote the use of natural gas for power production:

- The government has begun to charge fees for emissions of sulphur dioxide and nitrogen oxides, which are greater for coal-fired plants than gas-fired plants. In 2003, the State Council raised the emissions fee by a factor of ten for sulphur dioxide and applied the same emissions fee to nitrogen oxides, which had not been taxed before.
- Serious power shortages in 2003 revealed that coal supplies can be constrained by transportation capacity and that coal prices, while low, can rise. The official price of coal to electricity producers in each region was raised that year by 12 yuan (US$1.45)/tonne, and the electricity tariff was raised by 0.007 yuan/kWh to compensate.
- Gas supply options are expanding. The West-to-East gas pipeline, which can carry 12 Bcm/year, was recently completed. LNG terminals in Guangdong province will have the capacity to ship in another 8.2 Bcm/annum by 2008.
- The central government is trying to promote power generation from gas by administrative means, such as forbidding new coal-fired plants near large cities and requiring that gas be used at urban cogeneration facilities. According to the Power Industry Tenth Five-Year Plan, 23 gas-fired plants with a capacity of more than 20 GW are to be completed by 2010, raising gas use for power generation to 24 Bcm. Gas-fired plants should account for 11% of new generating capacity built between 2001 and 2010, making up 5% of total capacity by 2010. In some scenarios, the power sector share of China's gas consumption could rise to nearly 30% by 2010 and could further rise to 40–45% by 2020 in order to limit carbon emissions (Gao, 2003; SETC, 2002).

On the other hand, several factors may slow the use of natural gas for power production:

- Gas is costly and provided through take-or-pay contracts, so that losses would be heavy if a gas-fired plant went out of service and could not use its contracted gas.
- Expanded gas use in the power sector is likely to be supplied mainly through imports, with attendant uncertainty about prices and availability.
- Gas is very clean and can therefore be used directly in homes and businesses, whereas coal requires

large-scale processing to be used cleanly at a reasonable cost. Gas may thus be more economical than coal for clean, small-scale fuel use, while large-scale clean coal technologies in the power sector are cheap enough that gas cannot compete with coal for power without very high pollutant emissions charges.

- Under traditional regulation of the electric power industry, there is political pressure for the government to keep the price of electricity as low as possible, both for individual citizens and for businesses competing in international markets. This in turn creates pressure for power producers to use the lowest-cost means of production, namely coal, regardless of ancillary benefits associated with gas.
- With planned deregulation of electricity generation to boost competition in the power sector, the pressure to use the lowest-cost means of production will be even greater, unless there are special mechanisms to compensate for the higher costs of alternative fuels, such as subsidies for certain types of power plants or portfolio standards requiring that some types of plants produce a target share of generation.

For the most part, China's programmes of construction for hydropower and nuclear power plants appear to be set, at least for the next two decades, by planning authorities. Yet since the construction programmes are so ambitious, there is relatively limited scope for accelerating them. So much of the debate about the medium- and long-term future of China's electric power sector relates to the relative roles of coal, the reliable standby, and gas, the clean but expensive newcomer.

The costs of conventional coal-fired and gas-fired power plants are compared below under various assumptions about fuel costs, exchange rates, and the value of reducing carbon emissions. The costs of conventional fossil-fuelled plants and of fossil-fuelled plants with carbon sequestration are also compared under various assumptions about charges for carbon emissions. Each of the main components of generating costs is explained in turn: capital costs, fuel costs, operation and maintenance costs, and environmental charges. Since the comparison relates to construction of new plants, coal-fired plants are assumed to be late-model plants with flue-gas desulphurisation (FGS) equipment, and gas-fired plants are assumed to be high-efficiency combined-cycle gas turbine plants.

3. Capital costs of fossil-fuelled power plants in China

The capital cost component of generating costs for power plants depends on several factors:

- The capital construction cost per kilowatt of generating capacity, CC.
- The cost of capital, or discount rate, r, which together with the amortisation period determines the percentage of construction costs that must be paid back each year.
- The plant amortisation period in years, n, which equals the physical lifetime of the plant in economic terms but may be shorter in financial terms since banks often require that loans be repaid in less than the physical lifetime of the plant.
- The capacity factor, CF, the ratio of actual output to rated output in a typical year, often stated in terms of numbers of hours of operation per year at full capacity.

Multiplying the capital cost/kilowatt of capacity times the amortisation factor, which is the percentage of capital that must be paid each year in order for the sum of the discounted payments to equal the capital cost, one obtains the amount of principal repayment, PR, required per kilowatt of capacity each year:

$$PR = CC \times r(1+r)^n/[(1+r)^n - 1].$$

Dividing that annual principal repayment, in dollars per kilowatt, by the average number of hours of operation each year, one obtains the capital cost, K, in dollars per kilowatt-hour:

$$K = \{CC \times r(1+r)^n/[(1+r)^n - 1]\}/\{8760 \times CF\}.$$

Gas turbines have been getting cheaper as technology develops and their market expands:

- Fig. 1 plots the cost and efficiency of gas turbines recently built around the world. For the 81 turbines shown, efficiency averaged 33% and cost averaged US$342/kW. For many turbines built recently, efficiency rose to around 35% and the cost had declined to around $200/kW.

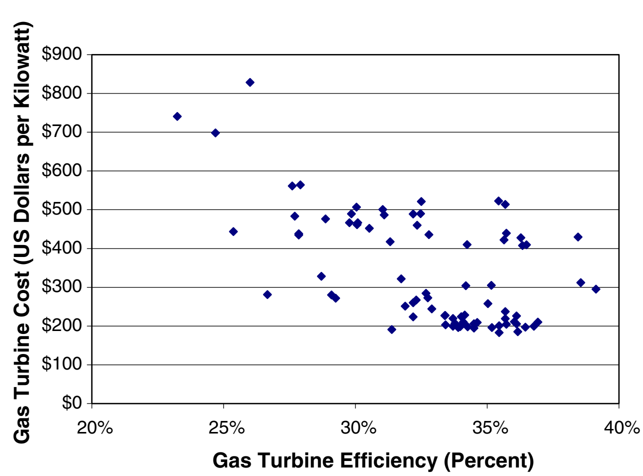

Fig. 1. Scatter plot of cost and efficiency of new gas turbines around the world.

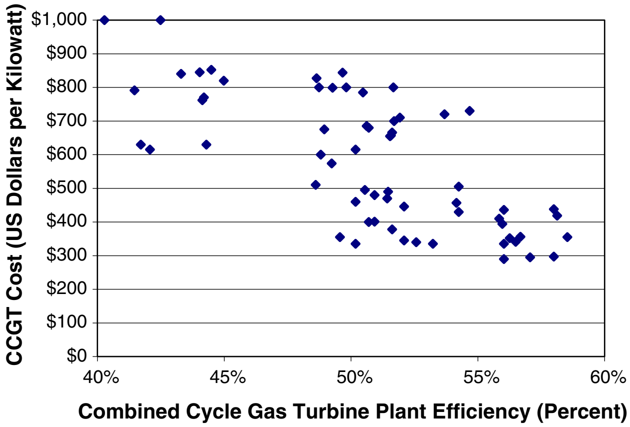

Fig. 2. Cost and efficiency of combined cycle gas turbine power plants: scatter plot for recently built CCGT plants around the world.

- Fig. 2 plots the cost and efficiency of combined cycle gas turbine power plants, which include a gas turbine plus equipment that utilises exhaust heat from the gas turbine, thereby raising overall conversion efficiency. For the 63 plants shown, the average efficiency was 51% and the average investment cost was $575/kW. For many combined cycle plants built recently, the efficiency had improved to over 55% and the cost had declined to about $400/kW.
- Looking at the charts together, one sees that the gas turbine cost represents about half the total capital cost for CCGT plants (China Energy Network, 2003a, b).

Base-case capital cost assumptions for coal and gas-fired plants can be made as follows:

- Costs of US$523/kW for a new coal plant that consists of two 600 MW units with FGS (the average cost for 11 such coal plants recently built in China) and $526/kW for two new combined cycle gas plants that each consist of two 300 MW units (the average cost for four recent plants in China) as suggested by recent survey data (Hitachi Engineering Company, 2003);
- A 10% discount rate or weighted cost of capital;
- A 25-year financial lifetime for both coal-fired and gas-fired power plants;
- A capacity factor of 75.9% for both coal-fired and gas-fired power plants, corresponding to 6650 h in full service out of 8760 h in the year.

It may be noted that the assumed base-case construction cost for combined cycle gas turbines is substantially higher than the cost of such turbines recently built elsewhere. One reason is that all large-scale gas turbines, which are high-technology equipment, must be imported; while exempted from import tax, their purchase may entail high transaction costs. Other reasons include lack of experience in CCGT plant construction, high management costs, and high training costs.

Sensitivity cases for comparing capital costs of coal and gas plants may be derived as follows:

- *Lower-cost, higher-efficiency gas plants*: Based on worldwide data shown in Fig. 2, it may be possible to buy combined cycle gas plants with 58% efficiency at $300/kW. Such substantially reduced costs would naturally tend to make gas plants more economically attractive relative to coal plants.
- *Low discount rate*: It might be possible to obtain capital at a real cost of 5% per annum if the government reduced risks through loan guarantees. This would tend to boost the relative attractiveness of plants with higher capital costs per kilowatt, which will be coal-fired power plants under most reasonable assumptions.
- *Stronger currency*: The Chinese yuan could conceivably double in value against a trade-weighted basket of currencies over the next two decades. Since the capital costs of coal plants are encountered almost entirely within the domestic economy, and initially denominated in yuan, this would imply a doubling of capital costs per kilowatt for such plants in dollar terms. Since about half the capital cost of combined cycle gas plants consists of the cost of the gas turbine, as shown above, and since the gas turbine is imported, half the cost of such plants would remain constant, so that the overall costs of such plants would rise by just half in dollar terms. A stronger currency would thus tend to make gas plants more attractive.
- *Economic lifetimes*: In reality, coal-fired power plants have historically proven more durable than gas-fired plants. If the amortisation period is based on physical lifetimes of 40 years for coal plants and 20 years for gas plants, instead of financial lifetimes of 25 years for both types of plants, annual payments will decline for coal plants and increase for gas plants, tending to make coal plants more attractive.

Results of various capital cost comparisons for coal- and gas-fired plants are shown in Table 2. Under base-case assumptions, capital costs for the two types of plants are equal. But under most plausible alternative assumptions, capital costs for gas-fired plants are substantially lower.

4. Fuel and operating costs for fossil power plants in China

The fuel cost component of generating costs for power plants depends on several factors:

Table 2
Estimated capital costs of new coal- and gas-fired power plants in China

Plant type and cost assumptions	Capital cost/kW	Discount rate (%)	Plant lifetime (years)	Annual payback (%)	Annual hours	Capital cost/kWh
Coal base case	$523	10	25	11.02	6650	$0.0087
Gas base case	$526	10	25	11.02	6650	$0.0087
Gas low cost	$300	10	25	11.02	6650	$0.0050
Coal low discount rate	$523	5	25	7.10	6650	$0.0056
Gas low discount rate	$526	5	25	7.10	6650	$0.0056
Gas low discount rate, low cost	$300	5	25	7.10	6650	$0.0032
Coal high Yuan	$1046	10	25	11.02	6650	$0.0173
Gas high Yuan	$789	10	25	11.02	6650	$0.0131
Gas high Yuan, low cost	$450	10	25	11.02	6650	$0.0075
Coal 40-year lifetime	$523	10	40	10.23	6650	$0.0080
Gas 20-year lifetime	$526	10	20	11.75	6650	$0.0093
Gas 20-year lifetime, low cost	$300	10	20	11.75	6650	$0.0053

- Physical unit cost, PCU, in dollars per tonne of coal or dollars per thousand cubic metres of gas.
- Heat content of fuel per physical unit, HC, in million British thermal units (MBtu) per tonne of coal or MBtu per thousand cubic metres of gas;
- Efficiency, e, with which fuel is burned in the generating plant, or the fraction of the fuel's energy content that is converted to energy in the form of electricity, where 100% conversion efficiency would yield 1 kWh for every 0.003412 MBtu of fuel input.

The fuel cost, F, in dollars per kilowatt-hour, can then be expressed by the following formula:

$$F = [\mathrm{PCU}/\mathrm{HC}] \times [0.003412/e].$$

Coal prices are generally lower in China than in other economies, but they vary substantially. Fig. 3 shows how coal prices to electricity generators compare for various parts of China and the world over time. China's average steam coal price in 2002 was 136 yuan or US$16.50/tonne, but transportation costs raised the average price for power plants to 210 yuan or $25.30/tonne. As the figure shows, 2002 power sector coal prices varied considerably, from $20 to $45/tonne. Delivered power sector prices were relatively high in the south and east, generally above $35/tonne, and lower in the north and northeast, at or below $30/tonne.

Natural gas in China is much more expensive than coal. Domestic resources are located in remote areas with high development costs. Thus, expansion of gas use will require imports of cheaper gas from abroad, through pipelines or LNG terminals. Gas from the West-to-East pipeline is priced at 1.1–1.2 yuan/m^3, depending on the location of delivery, including well-head cost of 0.48 yuan/m^3 and transportation charges to power plants (IEA, 2003; Chang, 2003). This converts (at 8.3 yuan/dollar and 0.036 MBtu/m^3) to a range of US$3.68 to $4.02/MBtu. The contract price for LNG delivered to ports in Guangdong is lower, just $3/MBtu (Cui et al., 2003; Schneider, 2003).

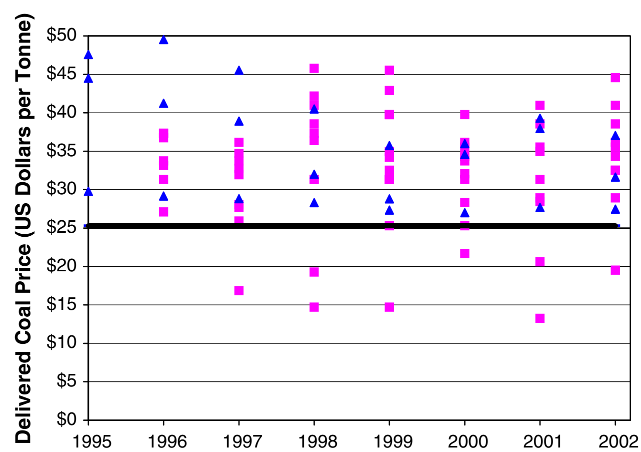

Fig. 3. Delivered coal price to electricity generators in China and elsewhere.

Base-case fuel cost assumptions for coal- and gas-fired plants can now be made as follows:

- Physical costs of 1.15 yuan or $0.1386/m^3 for natural gas (the price midpoint for gas from the West-to-East Pipeline), 230 yuan or $25.30/tonne of coal on average, and $45.00/tonne of coal in the areas furthest from coal mines.
- Heat content of 0.036 MBtu/m^3 of gas and 21.82 MBtu/tonne of coal.
- Resulting costs of $3.85/MBtu for gas, $1.16 for coal delivered to power plants on average, and $2.06 for coal delivered to power plants far from coal mines.
- Efficiencies of 36% for coal plants and 50% for gas plants, implying heat rates of 9478 Btu/kWh for coal plants and 6824 Btu/kWh for gas plants.

Sensitivity cases for comparing the fuel costs of coal and gas plants may be derived as follows:

- *Lower gas fuel cost*: A plant located on the coast might be able to obtain gas more cheaply, perhaps as low as the LNG price of $3/MBtu in Guangdong. Cheaper gas might help gas plants compete more effectively against coal plants.
- *Higher gas plant efficiency*: The most efficient gas-fired power plants have operated at efficiencies as high as 58%, reducing fuel costs per kilowatt-hour.

Results of various fuel cost comparisons for coal- and gas-fired plants are shown in Table 3.

Maintenance costs for power plants are typically estimated as a function of capital costs. The more equipment there is at the plant, the more maintenance is required. As a rule of thumb, total maintenance costs may be assumed to equal 2.5% of the capital cost for a typical plant. So such costs can be approximated simply by multiplying the capital cost figures in Table 2 by 0.025. Under base-case assumptions, the maintenance costs would work out to roughly $0.00022/kWh for coal-fired and gas-fired plants alike. Under alternative assumptions, the type of plant with a capital cost advantage will have a proportionate but much smaller maintenance cost advantage.

Manpower and other operating costs at power plants are usually fixed amounts per plant per year. This analysis assumes annual operating costs of US$1.32 million for coal plants and US$1.02 million for gas plants with 1200 MW of capacity. Operating 6650 h/year, this amount of capacity will generate 7.98 billion kWh/year. Dividing by that number of kilowatt, operating costs are found to be $0.0001654/kWh for coal plants and $0.0001278/kWh for gas plants. These amounts are obviously quite negligible compared with other cost components.

5. Environmental charges for power plants in China

China has instituted charges on emissions of major atmospheric pollutants from all sources, with effect from July 2004 for nitrogen oxides and from July 2003 for other pollutants including sulphur dioxide, dust, carbon monoxide, mercury and soot. A standard fee of 0.6 yuan is levied on each unit of "pollutant standard equivalent" (PSE). The more powerful the pollutant, the less of it is needed to constitute one PSE. For example, while 16.7 kg of carbon monoxide are needed to equal one PSE, just 0.0001 kg of mercury is needed. The fees now in place for various pollutants, the amount of pollutant per PSE, and the equivalent charge per kilogram of pollutant are shown in Table 4. Each facility currently pays fees on its top three pollutants in terms of PSEs; for electric power plants, these are sulphur dioxide, nitrogen oxides and dust.

Table 3
Estimated fuel costs of new coal- and gas-fired power plants in China

Plant type and cost assumptions	Fuel cost/unit	Fuel MBtu/unit	Fuel cost/ MBtu	Plant efficiency (%)	Heat Rate (Btu/kWh)	Fuel cost/ kWh
Coal base case, average	$25.30/t	21.82 MBtu/t	$1.16	36	9478	$0.0110
Coal base case, high	$45.00/t	21.82 MBtu/t	$2.06	36	9478	$0.0195
Gas base case	$0.1386/m^3	0.036 MBtu/m^3	$3.85	50	6824	$0.0263
Gas low fuel cost	$0.1080/m^3	0.036 MBtu/m^3	$3.00	50	6824	$0.0205
Gas high plant efficiency	$0.1386/m^3	0.036 MBtu/m^3	$3.85	58	5882	$0.0226
Gas low cost, high efficiency	$0.1080/m^3	0.036 MBtu/m^3	$3.00	58	5882	$0.0176

Table 4
Fees on emissions of atmospheric pollutants in China

Pollutant	Fee/unit pollutant standard equivalent (Yuan/PSE)	Kg pollutant/pollutant standard equivalent	Fee/kg of pollutant
Sulphur dioxide (SO_2)	0.6	0.95 kg SO_2/PSE	0.632 yuan/kg SO_2
Nitrogen oxides (NO_x)	0.6	0.95 kg NO_x/PSE	0.632 yuan/kg NOx
Dust	0.6	4.0 kg Dust/PSE	0.150 yuan/kg Dust
Carbon monoxide (CO)	0.6	16.7 kg CO/PSE	0.036 yuan/kg CO
Mercury (Hg)	0.6	0.0001 kg Hg/PSE	6,000 yuan/kg Hg
Soot	0.6	2.18 kg Soot/PSE	0.275 yuan/kg Soot

Source: SEPA (2003).

Regulations also require that all new coal-fired power plants install FGD equipment. At present, the fee per unit of SO_2 emissions is deliberately set to equal the estimated cost per unit of desulphurisation, so that the installation of FGD "scrubbers" no longer carries an effective penalty. In future, the fee per unit of SO_2 emissions may be raised so that there is actually a positive financial incentive for the installation of desulphurisation equipment.

Table 5 shows the current impact of emissions charges on sulphur dioxide (Liu, 2003), as well as nitrogen oxides and dust (Logan, 1999; Logan and Luo, 1999), on the cost per kilowatt-hour of electricity from coal- and gas-fired power plants. For each pollutant, the charge per kilowatt-hour is calculated by multiplying an emission factor in kilogram per kilowatt-hour by the emissions charge per kilogram from the preceding table, assuming currency conversion of 8.3 yuan/dollar. Total environmental charges are less than \$0.0016/kWh for coal plants and \$0.00004/kWh for gas plants. If the value of the yuan were to double, the environmental charges expressed in dollar terms would also double, to \$0.0031/kWh for coal plants and nearly \$0.0001/kWh for gas plants. While the charges are quite small at present, they might well increase in the future if public health concerns persist.

With growing concerns over global warming, charges might eventually be imposed on carbon dioxide emissions, creating incentives to install carbon sequestration technology if available. Table 6 shows the additional capital costs that would be incurred for the installation of carbon sequestration equipment under the various assumptions made earlier for basic capital costs. According to recent technical estimates, technology for carbon sequestration might be made available within the next two decades at an extra cost of US\$840/kW for coal plants and \$380/kW for gas plants, with 80% sequestration at coal plants and 85% sequestration at gas plants (Freund, 2002). If the sequestration equipment were assumed to be manufactured half within China and half in other economies, a doubling of China's currency value per the "high yuan" sensitivity cases would increase the effective cost, in dollar terms, by half for both types of plants.

Table 7 shows carbon charges per kilowatt-hour for coal and gas plants, with and without carbon sequestra-

Table 5
Environmental charges on coal- and gas-fired power plants in China

Type of charge and plant and other assumptions	Emissions (kg/kWh)	Emissions charge/ kg	Emissions charge/kWh
SO_x charge, coal plant	0.01737	\$0.07609	\$0.001322
NO_x charge, coal plant	0.00030	\$0.07609	\$0.000228
NO_x charge, gas plant	0.00005	\$0.07609	\$0.000038
Dust charge, coal plant	0.00020	\$0.01807	\$0.000004
Dust charge, gas plant	0.00005	\$0.01807	\$0.000001
Total charge, coal plant			\$0.001554
Total charge, gas plant			\$0.000039

Table 6
Incremental capital costs for carbon sequestration at hypothetical advanced technology coal- and gas-fired power plants

Plant type and cost assumptions	Extra capital cost/kW	Discount rate (10%)	Plant lifetime (years)	Annual payback (10%)	Annual hours	Extra capital cost/kWh
Coal base case	\$840	10	25	11.02	6650	\$0.0139
Gas base case	\$380	10	25	11.02	6650	\$0.0063
Gas low cost	\$380	10	25	11.02	6650	\$0.0063
Coal low discount rate	\$840	5	25	7.10	6650	\$0.0090
Gas low discount rate	\$380	5	25	7.10	6650	\$0.0041
Gas low discount rate, low cost	\$380	5	25	7.10	6650	\$0.0041
Coal high Yuan	\$1260	10	25	11.02	6650	\$0.0209
Gas high Yuan	\$570	10	25	11.02	6650	\$0.0094
Gas high Yuan, low cost	\$570	10	25	11.02	6650	\$0.0094
Coal 40-year lifetime	\$840	10	40	10.23	6650	\$0.0129
Gas 20-year lifetime	\$380	10	20	11.75	6650	\$0.0067
Gas 20-year lifetime, low cost	\$380	10	20	11.75	6650	\$0.0067

Table 7
Hypothetical charges for power plant carbon emissions

Plant type and cost assumptions	No sequestration, CO_2 fee of			Sequestration, CO_2 fee of		
	Zero	\$20/tonne	\$100/tonne	Zero	\$20/tonne	\$100/tonne
Coal base case (36% efficiency)	\$0.0000	\$0.0176	\$0.0880	\$0.0000	\$0.0035	\$0.0176
Gas base case (50% efficiency)	\$0.0000	\$0.0074	\$0.0370	\$0.0000	\$0.0011	\$0.0055
Gas low cost (58% efficiency)	\$0.0000	\$0.0064	\$0.0319	\$0.0000	\$0.0010	\$0.0048

Table 8
Estimated total costs of new coal- and gas-fired powerplants in China

Plant type and cost assumptions	Capital cost/kWh	Fuel cost/kWh	O and M cost/kWh	Pollutant cost/kWh	Total cost/kWh
Coal base case, high cost	\$0.0087	\$0.0195	\$0.0004	\$0.0016	\$0.0301
Coal base case, average cost	\$0.0087	\$0.0110	\$0.0004	\$0.0016	\$0.0216
Gas base case, average cost	\$0.0087	\$0.0263	\$0.0003	\$0.0000	\$0.0354
Gas base case, low cost	\$0.0050	\$0.0176	\$0.0003	\$0.0000	\$0.0229
Coal low discount rate, high cost	\$0.0056	\$0.0195	\$0.0003	\$0.0016	\$0.0269
Coal low discount rate, average cost	\$0.0056	\$0.0110	\$0.0003	\$0.0016	\$0.0184
Gas low discount rate, average cost	\$0.0056	\$0.0263	\$0.0003	\$0.0000	\$0.0322
Gas low discount rate, low cost	\$0.0032	\$0.0176	\$0.0002	\$0.0000	\$0.0210
Coal high Yuan, high cost	\$0.0173	\$0.0390	\$0.0008	\$0.0031	\$0.0602
Coal high Yuan, average cost	\$0.0173	\$0.0220	\$0.0008	\$0.0031	\$0.0432
Gas high Yuan, average cost	\$0.0131	\$0.0263	\$0.0006	\$0.0001	\$0.0400
Gas high Yuan, low cost	\$0.0075	\$0.0176	\$0.0004	\$0.0001	\$0.0256
Coal 40-year lifetime, high cost	\$0.0080	\$0.0195	\$0.0004	\$0.0016	\$0.0295
Coal 40-year lifetime, average cost	\$0.0080	\$0.0110	\$0.0004	\$0.0016	\$0.0210
Gas 20-year lifetime, average cost	\$0.0093	\$0.0263	\$0.0004	\$0.0000	\$0.0360
Gas 20-year lifetime, low cost	\$0.0053	\$0.0176	\$0.0003	\$0.0000	\$0.0232

tion, under various assumptions about carbon dioxide emission fees. For coal plants, CO_2 emissions are assumed to be 880 g/kWh without sequestration and 176 g/kWh with 80% sequestration. For base-case gas plants, CO_2 emissions are 370 g/kWh without sequestration and 55 g/kWh with 85% carbon sequestration. For high-efficiency gas plants, CO_2 emissions are 319 g/kWh without sequestration and 48 g/kW h with 85% sequestration (Freund, 2002).

6. Total cost (TC) comparison for power plants in China

Based on the foregoing analysis, it is possible to make an overall cost comparison of gas-fired and coal-fired power plants in China, under a variety of assumptions. The TC is the sum of capital cost K, fuel cost F, operating and maintenance cost OM, and environmental charges EC, where each is expressed in dollars per kilowatt-hour:

$$\mathrm{TC} = K + F + \mathrm{OM} + \mathrm{EC}.$$

In this section, the total generating costs will be compared first under current conditions and then considering charges that might be imposed on carbon dioxide emissions, with and without carbon sequestration technology.

Table 8 compares the total generating costs of coal- and gas-fired plants by summing up the data shown earlier for capital costs in Table 2, fuel costs in Table 3, and environmental charges in Table 5, as well as operating and maintenance costs. The basic scenarios in terms of capital cost and financial assumptions are similar to those already described in the section on capital costs:

- *Base case*: Financial assumptions include a 10% discount rate, a 25-year financial lifetime for both coal- and gas-fired plants, and a capacity factor of 75.9% for both types of plants, corresponding to 6650 h/year in service.
- *Low discount rate*: Capital can be obtained at a 5% discount rate.
- *Strong currency*: The yuan doubles in value against the US dollar over the long term. In dollars, this doubles the capital, fuel and operating costs of coal-fired plants, which are assumed to be incurred entirely within the domestic economy. The capital cost of gas

plants, about half of which is attributed to imported turbines, would increase by half, while gas fuel, assumed to be entirely imported, would not change in value, and operating costs would double for gas plants as for coal plants. Hypothetical carbon sequestration technology is assumed to be half domestic and half imported, increasing in costs in dollar terms by half.
- *Economic lifetimes*: Coal and gas plants are amortised over their likely physical lifetimes of 40 and 20 years, respectively, instead of over a 25-year financial lifetime.

Within each scenario, four separate cost cases are developed:

- *Average-cost coal*: Coal plants have a capital cost of \$523/kW at current exchange rates, a fuel cost of \$25.30/tonne (\$1.16/MBtu) equal to the average cost of coal to power producers in 2002, and an efficiency of 36%.
- *Average-cost gas*: Gas plants have a capital cost of \$526/kW at current exchange rates, a fuel cost of \$3.85/MBtu equal to the average cost of power producers of gas from the West-to-East pipeline, and an efficiency of 50%.
- *High-cost coal*: Coal plants are located far from coal mines, with fuel cost of \$45/tonne instead of \$25.30/tonne (\$2.06/MBtu instead of \$1.16/MBtu)
- *Low-cost gas*: Gas plants have a lower capital cost per kilowatt at current exchange rates (\$300/kW instead of \$526/kW), a lower fuel cost (\$3.00/MBtu instead of \$3.85/MBtu), and higher efficiency (58% instead of 50%).

Several observations may be made from the data presented in Table 8:

- *Base case*: With average gas and coal plant costs, total generating cost is 64% higher for gas than coal, appearing to confirm the basic wisdom that gas cannot effectively compete. But with lower gas costs (including assumptions about lower plant capital costs, lower fuel costs, and higher plant efficiency) and higher coal costs (representing likely costs in regions more remote from coal mining areas), gas-fired power could have as much as a 24% cost advantage. Thus, the possibility of niche markets for gas-fired generation within China's economy cannot be ruled out, especially in coastal areas near gas and far from coal.
- *Low discount rate*: The situation is little altered from the base case. For average coal and gas plants, costs per kilowatt are virtually identical, so costs per kilowatt-hour are affected in almost the same way by a reduced cost of capital. Even with lower gas plant costs per kilowatt, capital costs do not make up a large enough share of TCs for a lower cost of capital to improve the relative position of gas by much.
- *Economic lifetimes*: Again, the situation is little changed from the base case. Extending the amortisation period to 40 years for coal plants and reducing it to 20 years for gas plants has little impact on annualised capital costs or costs per kilowatt-hour.
- *Strong currency:* A doubling of the yuan's value could make gas-fired power plants far more competitive, giving them a slight edge over coal-fired plants even under average cost conditions. Under low cost assumptions, gas plants could undercut coal-fired power in areas remote from coal production by more than half.

The picture changes considerably if carbon taxes are introduced and carbon sequestration technology becomes available. Table 9 compares the TCs of generation from coal-fired power plants both with and without carbon sequestration technology, assuming carbon taxes of zero, \$20 and \$100/tonne of CO_2. When carbon taxes are absent, the additional cost of installing carbon sequestration technology is obviously not warranted, and the competitive positions of coal and gas remain as they were before. But when carbon taxes reach \$20/tonne of CO_2, the impact is striking: costs are quite similar with and without sequestration, they are also often quite similar for both coal and gas plants, and the cost advantage of coal-fired power under average cost conditions nearly evaporates. When carbon taxes reach very high levels, carbon sequestration becomes imperative, and gas looks a lot better than coal in most instances.

Regarding the impact of a \$20 tax/tonne of carbon dioxide, the following may be observed:

- *Coal loses most of its cost advantage*: The cost premium for gas-fired power under average cost conditions narrows from 64% to 9% in the base case, from 75% to 10% with a low discount rate, and from 71% to 12% with amortisation of costs over physical lifetimes. In other cases, average cost conditions give gas-fired power a cost advantage of 16–22%.
- *Carbon sequestration begins to make sense*: For both coal and gas plants, sequestration clearly reduces costs in the low discount rate case, largely because the reduced cost of capital limits the financial burden of installing sequestration equipment. Sequestration has little effect on costs in the base case or in the economic lifetime case.
- *Gas could be favoured over sequestration in some cases*: In the strong currency case, a carbon tax at this level would render coal more expensive than gas for electricity generation, owing to its higher carbon

Table 9
Comparing hypothetical costs of coal- and gas-fired powerplants in China at various levels of carbon dioxide tax, with and without sequestration

Plant type and cost assumptions	Cost/kWh without sequestration			Cost/kWh with sequestration		
	Zero tax	$20/t tax	$100/t tax	Zero tax	$20/t tax	$100/t tax
Coal base case, high cost	$0.0301	$0.0477	$0.1181	$0.0444	$0.0479	$0.0620
Coal base case, average cost	$0.0216	$0.0392	$0.1096	$0.0359	$0.0394	$0.0535
Gas base case, average cost	$0.0354	$0.0428	$0.0724	$0.0419	$0.0430	$0.0474
Gas base case, low cost	$0.0229	$0.0292	$0.0548	$0.0293	$0.0303	$0.0341
Coal low discount rate, high cost	$0.0269	$0.0445	$0.1149	$0.0361	$0.0396	$0.0537
Coal low discount rate, average cost	$0.0184	$0.0360	$0.1064	$0.0276	$0.0311	$0.0452
Gas low discount rate, average cost	$0.0322	$0.0396	$0.0692	$0.0364	$0.0375	$0.0419
Gas low discount rate, low cost	$0.0210	$0.0274	$0.0529	$0.0252	$0.0262	$0.0300
Coal high Yuan, high cost	$0.0602	$0.0778	$0.1482	$0.0816	$0.0851	$0.0992
Coal high Yuan, average cost	$0.0432	$0.0608	$0.1312	$0.0646	$0.0681	$0.0822
Gas high Yuan, average cost	$0.0400	$0.0474	$0.0770	$0.0497	$0.0508	$0.0553
Gas high Yuan, low cost	$0.0256	$0.0320	$0.0575	$0.0353	$0.0362	$0.0400
Coal 40-year lifetime, high cost	$0.0295	$0.0471	$0.1175	$0.0427	$0.0462	$0.0603
Coal 40-year lifetime, average cost	$0.0210	$0.0386	$0.1090	$0.0342	$0.0377	$0.0518
Gas 20-year lifetime, average cost	$0.0360	$0.0434	$0.0730	$0.0429	$0.0440	$0.0484
Gas 20-year lifetime, low cost	$0.0232	$0.0296	$0.0551	$0.0301	$0.0310	$0.0349

content, but generation from gas would still be cheaper without sequestration than with it.

- *Gas would have a huge cost advantage in some areas*: This can be seen by comparing low cost gas-fired generation—involving plants with lower capital costs and fuel costs and higher operating efficiency—with high-cost coal-fired generation in areas remote from coal producing regions, in any of the cases shown.

With respect to the impact of a $100 tax/tonne of carbon dioxide, one can notice:

- Carbon sequestration technology becomes clearly advantageous in all cases.
- Gas is cheaper than coal for power generation in all cases as well.

Focusing on the base-case assumptions, charts can be used to illustrate how fuel prices and environmental charges affect the overall comparison between gas- and coal-fired plants. Fig. 4 shows how relative coal and gas prices affect the generating cost comparison when there are no emissions charges for carbon dioxide, with base-case assumptions about capital and operating costs:

- Assuming average gas costs of $3.85/MBtu, based on the delivered cost of gas from the West-to-East pipeline, coal-fired generation will be cost-competitive wherever coal can be obtained for less than $57/tonne.
- Assuming favourable gas costs of $3.00/MBtu, which might be obtained under optimistic conditions for LNG in coastal areas, coal-fired generation will only be cost-competitive if coal can be obtained for less than $43/tonne.

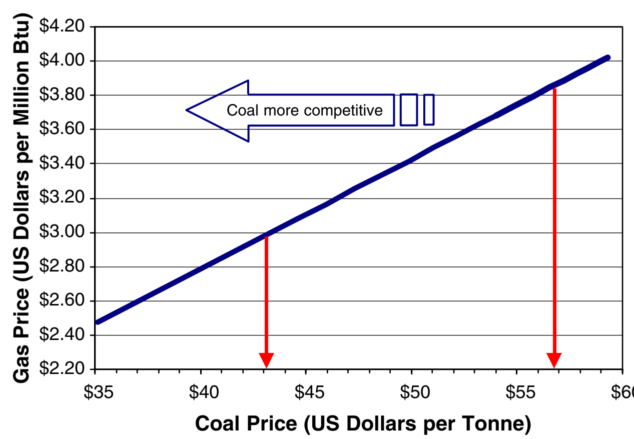

Fig. 4. Influence of coal and gas prices on whether coal-fired or gas-fired generation is most cost competitive under base-case assumptions.

As discussed above, average coal prices in China are around $25/tonne, so coal is usually very cost-competitive. But some coal prices, for coal-fired power plants far from coal mining areas, may range as high as $45/tonne, opening up some limited prospects for gas-fired power under current market conditions.

Fig. 5 shows how gas- and coal-fired power competes with each other, under base-case conditions with average fuel costs, when carbon taxes and carbon sequestration technology are introduced. The following basic cost assumptions are incorporated in the figure:

- Coal-fired generation *without* sequestration costs $0.0216/kWh prior to carbon fees, plus $0.00088/kWh/dollar of tax imposed per tonne of carbon dioxide.

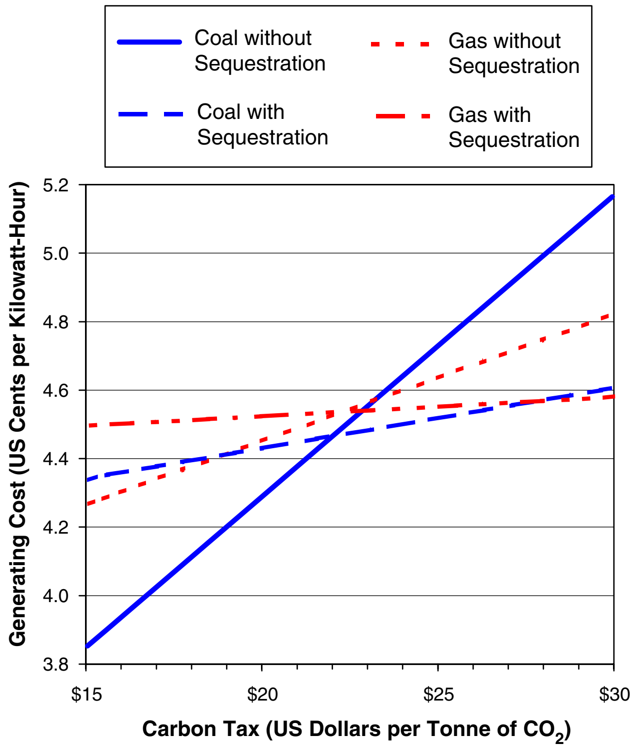

Fig. 5. comparative costs of coal and gas-fired power in China, with and without carbon sequestration, at various levels of carbon dioxide tax.

- Coal-fired generation *with* sequestration costs $0.0359/kWh prior to carbon fees, plus $0.000176/kWh per dollar of tax imposed per tonne of carbon dioxide. The cost increases just one-fifth as much per unit of tax since sequestration technology is assumed to remove four-fifths of the carbon emissions stream.
- Gas-fired generation *without* sequestration costs $0.0354/kWh prior to carbon fees, plus $0.00037/kWh per dollar of tax imposed per tonne of carbon dioxide.
- Gas-fired generation *with* sequestration costs $0.0419/kWh prior to carbon fees, plus $0.000055/kWh per dollar of tax imposed per tonne of carbon dioxide. The cost increases just 15% as much per unit of tax since sequestration technology is assumed to remove 85% of the carbon emissions stream.

The figure confirms that interesting things happen when CO_2 taxes exceed $20/tonne:

- When the CO_2 tax is below $22/tonne, the cheapest generating option under average fuel cost conditions is coal-fired power without sequestration.
- When the CO_2 tax is between $22 and $28/tonne, the cheapest option becomes coal with sequestration, followed closely by gas with sequestration, implying the latter option could well compete where coal is costlier than average.
- When the CO_2 tax exceeds $28/tonne, the cheapest option becomes gas with sequestration, though coal with sequestration follows closely up to a CO_2 tax of around $35/tonne and might thus still compete at that tax level in some areas.

7. Summary of conclusions

At present, coal-fired power holds a clear economic advantage over gas-fired power in China:

- *With average fuel prices and capital costs*, gas-fired power is roughly two-thirds more costly than coal-fired power per kilowatt-hour.
- *But under favourable conditions for gas*, gas-fired power could undercut coal-fired power in cost by nearly a quarter.
- *Sensitivity analysis* indicates that the cost comparison between coal- and gas-fired powers would be little changed by different assumptions about discount rates or plant lifetimes, but could be changed significantly by a stronger Chinese currency.

The economic comparison between coal- and gas-fired power in China could change with the introduction of carbon dioxide charges and carbon sequestration technology in the longer term:

- *With a charge of $20/tonne of carbon dioxide under average cost conditions*, gas-fired power would be only slightly more expensive than coal-fired power at current exchange rates and could be cheaper than coal-fired power if the yuan appreciates.
- *Carbon sequestration technology* could be economical with a carbon dioxide charge of $22/tonne or more under average fuel and capital cost conditions. Employing sequestration, coal- and gas-fired power would be similar in cost if a carbon dioxide charge of up to $35/tonne were imposed, but gas-fired power would enjoy a clear cost advantage at current fuel prices if the carbon dioxide charge were higher.

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