



WP2 – Future Energy Technology Perspectives

2.3 National Scenarios Analysis

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1 Introduction

Coal is China's primary fuel for power generation and will almost certainly remain so for the foreseeable future. At present China's installed capacity of power generation plant totals about 700GWe with over 70% of that based on coal. By 2020, capacity is projected to approximately double with coal still the dominant fuel. Although major Chinese programmes are in place to improve energy efficiency, increase deployment of renewable energy technologies and increase the installed capacity of nuclear plant, coal-fired power plants will continue to be built in large numbers for many years to come. This report presents the results of an energy systems analysis exercise using the China MARKAL model, to provide a perspective on the energy technologies that may be deployed in China to 2050 to meet its energy needs. The model also examines the cost and impact of deploying CCS in China.

Literature (Chen, et al, 2001-2007) provided previous China MARKAL modelling results. Since the Chinese economy has developed much faster than expected, almost all modelling results done to date including the China MARKAL modelling, provide lower projections for both energy and carbon emissions than the actual situation. Therefore it is necessary to update the assumptions on future social economic growth to generate new energy service demands for China MARKAL¹. Due to time constraints, this update of the energy service demand projection mainly focuses on the high energy-intensive industrial sectors such as iron and steel, cement, ammonia, and aluminium, and the transportation sector. The reasons for selecting these high energy-intensive sectors is that they share around 40% of total final energy consumption in China and most offer large stationary CO₂ emissions sources attractive for CO₂ capture. Although transportation now only shares 10% of total final energy consumption, it is expected to increase rapidly in future. This, combined with limited domestic oil reserves means that oil import dependency is projected to exceed 60% by 2020. To ensure energy security, a further aspect of this study considers the role of coal to liquefaction technology with capture to provide liquid synfuel for the transportation sector. It is uncertain at this stage, whether CTL will be deployed widely in China.

1.1 MARKAL

The MARKAL (Market allocation) model is a dynamic linear programming energy system optimization model which has been adopted to study China's future energy development strategy. MARKAL is based on a Reference Energy System (RES). It incorporates the full range of energy processes e.g. exploitation, conversion, transmission, distribution and end-use, and it is able to consider existing technologies as well as advanced technologies which may be deployed in future. The objective function of the model is to minimize energy system cost, including the capital costs of end-use (demand) technologies, capital costs of electricity generating technologies, fuel costs, infrastructure costs (such as pipelines), and operating and maintenance costs.

The China MARKAL model is developed in 5-year intervals extending from 2000 through 2050. It considers not only conventional fossil fuels such as coal, oil, natural gas, coal gas etc., but also new and renewable energy like hydro, nuclear, wind, solar, geothermal, and some synthetic fuels like methanol, DME etc. Current thermal power generation technologies, advanced thermal power generation technologies like IGCC, NGCC etc., new and renewable power generation technologies are included in China MARKAL. The process technologies include coal washing, coke making and oil refinery, as well as more advanced technologies such as coal gasification and coal liquefaction.

Five sectors, namely agriculture, industry, commercial, residential (divided into urban and rural) and transportation are considered in China MARKAL, which are further divided into several sub-sectors. For example, agriculture is divided into irrigation, farming, and agro-process; industry is divided into five energy intensive sub-sectors (iron and steel, cement production, ammonia, paper making, aluminium), non energy use, and other sectors; transportation sector is divided into freight and passenger transport, and they are further divided into railway, highway, waterway and air transport; urban and rural residential is divided into space heating, cooking and water heating, air conditioning,

¹ Energy service demands, as used here, refer to China's total demands for different 'energy services' like industrial production, heating and travel. These demands are expressed in units such as passenger-kilometres of car travel or m² of heated housing and are inputs to the MARKAL model. More details on the energy service demands used in the China MARKAL are available in the NZEC WP2 report '2.1 Future Energy Service Demands'

lighting and other electric appliances; commercial sector is divided into space heating and water heating, cooling, lighting and other electric appliances.

1.2 Approach

Energy systems analysis modelling by application of the China MARKAL energy model is used to determine the least-cost mix of technologies and fuels to meet the predicted energy service demands. This leads to the energy demands and energy mix, both in the demand and supply sides. Final energy demand and its mix, primary energy demand and its mix, power generation capacity and output and their mix, as well as carbon emissions from 2005 to 2050 will be analyzed.

Carbon constraints will then be added to the model and it will be asked to meet the same energy service demands while constrained to limit CO₂ emissions to a specified maximum level. Based on the specification of the NZEC project, the focus would be on running scenarios that might exclude CCS, those that might include CCS to differing extents and variations to the take-up of competing technologies. This analysis will provide an indication of the differences in marginal carbon cost. The model will also be used to assess the role of CCS in cutting carbon emissions.

Like almost all energy system optimization models, energy service demand (as opposed to *energy demand*) or activity level is the input to the model, thus standard MARKAL cannot reduce the fixed energy service demand to meet a certain carbon constraint target. The model changes the mix of technologies or fuels used (including both demand-side and supply-side technologies) in response to emissions constraints. Final energy demand might reduce because more efficient technologies are chosen. Another version of the MARKAL family of models, known as MARKAL-ED (elastic demand), can be used to assess the response of both energy service demand and technology/fuel to carbon reduction. But the challenge is determining the price and income elasticity for each end-use demand sector.

This then is an example of a modelling study that can provide insight into the possible role of CCS in a carbon constrained future scenario. Data availability is in part subjective due to limitations. Key assumptions made during the modelling are detailed. The results should therefore be considered indicative of the kind of outputs possible using this type of modelling approach. Further work will be worthwhile and should build upon the research and conclusions presented here. Suggestions of further work are presented in Section 6.

2 Assumptions

2.1 Assumptions on future social economic growth and energy service demand projection results

The main assumptions on future social and economic growth used to update the energy service demand in China MARKAL are shown in Table 1.

Table 1 Assumptions on future social and economic growth (NZEK Project Analysis 2009; ERI (Energy Research Institute, 2005); ESR (He Jiankun and et al, 2007); NIC (National Information Centre, 2003); DRC (Development Research Center, 2005); TU2005(Chen Wenying and et al, 2005).²

	2005	2010	2020	2030	2040	2050
GDP/Billion 2000US\$	1926	2970	6411	11481	17830	25151
GDP/Billion RMB	15793	24354	52570	94144	146206	206238
Population/ Million	130.8	137	145.4	148.3	148.3	144
Urbanization rate/%	42.3	45.7	53.7	60.8	66.8	72.2
Industrial structure						
Primary/%	12.50	8.73	4.96	3.18	2.25	1.71
Secondary/%	47.50	46.08	43.73	40.89	38.32	36.12
Tertiary/%	40.00	45.19	51.30	55.93	59.43	62.17

Chinese GDP is expected increase from 1198 billion dollars in 2000 to 25151 billion dollars in 2050, with an average annual growth rate of 6.28%. It will be 6411 billion dollars in 2020, 5.4 times what is was in 2000. GDP per capita will increase from 945 dollars in 2000 to 17109 dollars in 2050, with an average annual growth rate of 6.28%. With continued economic development, it is expected that China's industrial structure will adjust following the trend seen in most developed countries. Thus, it is expected that the proportion of primary and secondary industry will drop to 1.7% and 36.1% respectively, while the proportion of the service industry will rise to 62.2 % by 2050. From 1978 to 2006, China's urbanization rate increased from 17.9% to 43.9%, with an average annual growth rate of 3.25%. With the rapid development of the economy and the constant adjustment of industrial structure, China's urbanization will continue to develop rapidly and it is expected to reach 72% by 2050, which is equivalent to the current level of moderately developed countries.

Using the above mentioned assumptions, the Gompertz model is used to project future demand for iron and steel, cement, aluminium and ammonia, and also car ownership. The Gompertz model is described as following:

$$I = S \cdot e^{\alpha \cdot e^{-\beta \cdot PGDP}}$$

Where I is per capita demand for industrial products like iron & steel, cement, aluminium and ammonia, or car ownership; PGDP is GDP per capita; S is the saturation level of per capita demand for industrial products or car ownership. The saturation level for different industrial products and car ownership is determined based on reviews on related data in OECD countries especially the USA. And the

² For further information on the growth assumption used please see associated NZEK WP2 report '2.1 Future Energy Service Demands'

parameters α and β are determined based on regression analysis using related Chinese historical data from 1978 to 2006.

For freight and passenger transport except car, we also use Chinese historical data (1978-2006) to do regression analysis but without consideration of saturation. From the analysis, the relationships between transport turnover and GDP or per capita GDP are built.

When applying the Gompertz model to project future energy service demand, i.e. activity level, for the high energy-intensive sectors, one of the key issues is determining the saturation level. In this study it is based on a historical review on related data in OECD countries. The saturation level for steel is chosen as 0.5 tonnes production/capita according to the relationship between per capita steel production and per capita GDP in the OECD countries. Using a similar approach, the saturation levels for cement, ammonia and aluminium are determined on a tonnes of production per capita basis as 1.2 tonnes/cap, 0.05 tonnes/cap and 0.015 tonnes/cap respectively.

Figure 1 shows the projection results for the main industrial sectors. The annual growth rate of steel production during 1978 to 2000 was 6.56%, but it hit as high as 21.78% during 2000 to 2006 with elasticity of 2.15 and the production reached 419Mt in 2006. It is projected that steel production will peak at 742Mt by 2035. The annual growth rate for cement, aluminium and ammonia in the same period was 11%, 13% and 5% respectively, and it is projected that by 2035 the production of cement, aluminium and ammonia will peak at 1783Mt, 30Mt, 89Mt respectively.

Figure 1 Projection results for the high energy-intensive sectors

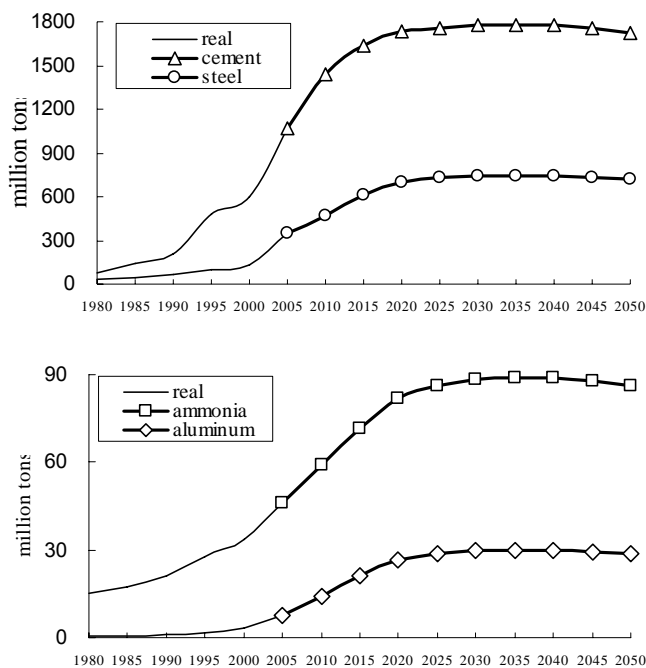
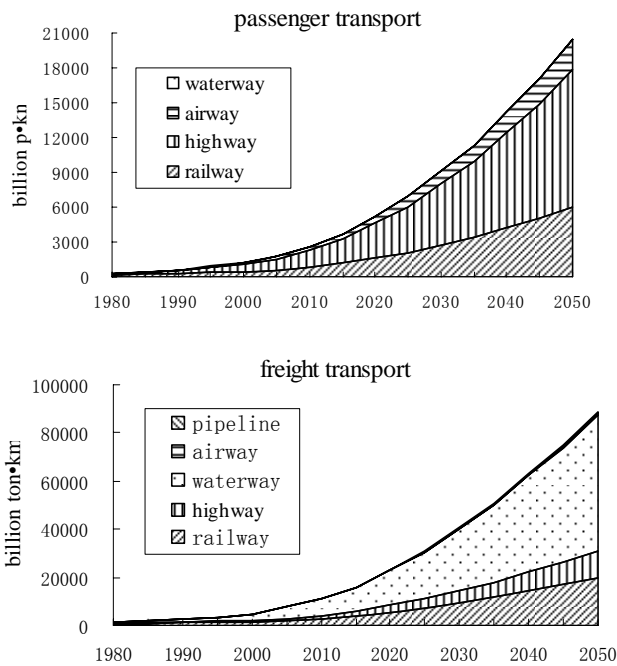


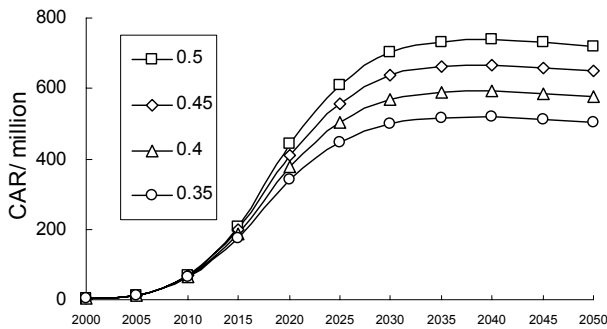
Figure 2 illustrates the projection results for future transport. In the past 28 years, China's transportation experienced rapid development with annual growth rates of 8.95% and 8.18% and elasticities of 0.92 and 0.84 for passenger and freight transport respectively. However, the passenger transport per capita was still only 1460 km in 2006, about one-tenth the IEA countries' average (IEA, 2007). Total passenger transport is expected increase from 1920 billion p•km to 20504 billion p•km by 2050 with passenger transport per capita of 17000 km, close to the current average level in IEA countries. As described in the NZEC WP2 Future Energy Service Demands Report, freight transport per GDP declined gradually from around 6 t•km/US\$2000 (exchange rate) in 1980 to 4.2 t•km/US\$2000 (exchange rate) in 2006. For international comparison, freight transport intensity is measured in t•km per PPP (IEA, 2007). If using PPP instead of exchange rate, Chinese freight intensity in 2006 would be around 1 t•km/US\$2000, close to the level seen in countries with large land areas such as USA, Canada and Australia. Freight transport is expected to maintain at around 4 t•km/US\$2000 (exchange rate) over the next 50 years, and the total freight transport will grow from 8895 billion t•km in 2006 to 88675 billion t•km by 2050.

Figure 2 Passenger and freight transport projection results



Car ownership in China was still very low in 2000, only 0.3 vehicles per 100 people, but grew very fast in last few years and reached around 1.4 vehicles per 100 people in 2006. The car ownership Gompertz model estimates that the number of private cars will peak at 665 million by 2035 with the assumption of saturation rate of 45 vehicles per 100 people. Figure 3 displays the projection results for cars based for different levels of saturation.

Figure 3 Projected future car numbers (millions)



2.2 Assumptions on main power generation technologies

Table 2 provides assumptions on the investment cost and efficiency for the main power generation technologies considered in the model (Chen, et al, 2001-2007). For all technologies except CCS the data are taken from the original China MARKAL and updated based both on discussion with experts and data in the literature (UNFCCC, 2006; 3E/Tsinghua, 2006). NZEC WP3³ have carried out case studies on capture for SC/USC, and the results show that the investment cost of power generation with capture is around 7000-9000 RMB/kW (1000US\$/kW-1300US\$/kW) before taking into account loan interest and tax, etc. Thus for SC/USC with capture technologies, we assume investment cost of 1400US\$/kW for the year 2010, 1200US\$/kW for 2020 and 1100US\$/kW for the year 2030 onwards. We also include IGCC with CCS in the model based on the author's own assumptions about cost. IGCC with capture is assumed to be 30% more expensive than IGCC without capture. In the model,

³ NZEC WP3 Carbon Dioxide Capture from Coal-Fired Power Plants in China Report

the investment cost for IGCC with capture is assumed to reduce from 1856US\$/kW in 2010 to 1400US\$/kW in 2020 and 1300US\$/kW for the year 2030 onwards.

Table 2 Assumptions on investment cost for the main power generation technologies (US\$/kW)

	2005	2010	2020	2030	2040	2050
SC/USC	600	600	600	600	600	600
SC/USC with capture		1400	1200	1100	1100	1100
IGCC	1428	1428	1100	1000	1000	1000
IGCC with capture		1856	1430	1300	1300	1300
NGCC ⁴	550	550	550	550	550	550
Nuclear	1500	1500	1500	1500	1500	1500
Hydro	1200	1200	1200	1200	1200	1200
Ohshore Wind	900	900	900	900	900	900
Offshore Wind	1500	1500	1500	1500	1500	1500
PV	2000	2000	2000	2000	2000	2000
Geothermal	1800	1700	1600	1500	1500	1500

We assume SC/USC's efficiency as 42% and SC/USC with capture as 32% with 10% energy penalty. This can be considered a conservative estimate as efficiencies of newly built USC plants may now reach 45%. For IGCC, efficiency is assumed as 45% and IGCC with capture is assumed as 37% with an energy penalty of 8%.

⁴ NGCC with CO₂ capture is not currently included as a technology option within China MARKAL

3 Reference Scenerio

3.1 Final energy consumption

The modelling shows that the final energy consumption is expected to grow from 1560Mtce in 2005 to 4833Mtce by 2050 in the reference case. The share of coal is expected to decrease significantly from 43.2% in 2005 to 20.7% by 2050, while the share of oil, gas, electricity and heat is expected to increase from 27.1%, 6.5%, 18.3% and 5% to 32.1%,16.9%, 23.3% and 7.1% respectively.

Figure 4 Final energy consumption by fuel in the reference scenario

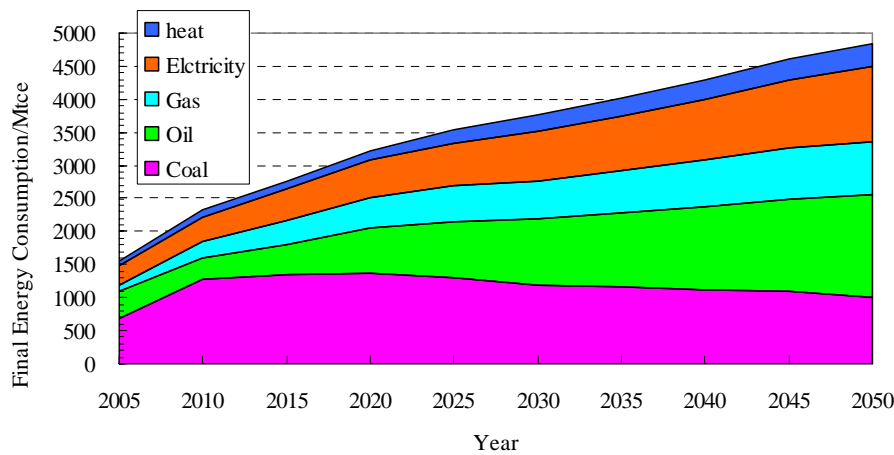
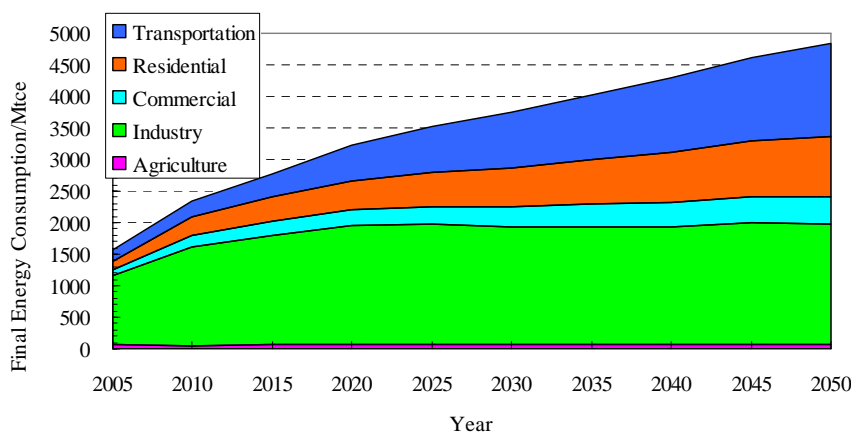


Figure 5 shows the final energy consumption by sector. The share of industry is expected to decrease from 70% in 2005 to only 40% by 2050, while transportation is expected to increase from 10% to 30%. The reason for the flat curve of the industry sector since 2020 is that demand for high energy-intensive products like steel and cement is expected to begin to peak around 2020 as shown in Figure 1. While China’s passenger transport per capita and car ownership are currently much lower than developed countries, they are expected to grow rapidly in future with improving living standards. Thus in line with projections displayed in Figure 2, the final energy consumption in transportation sector is expected to increase significantly.

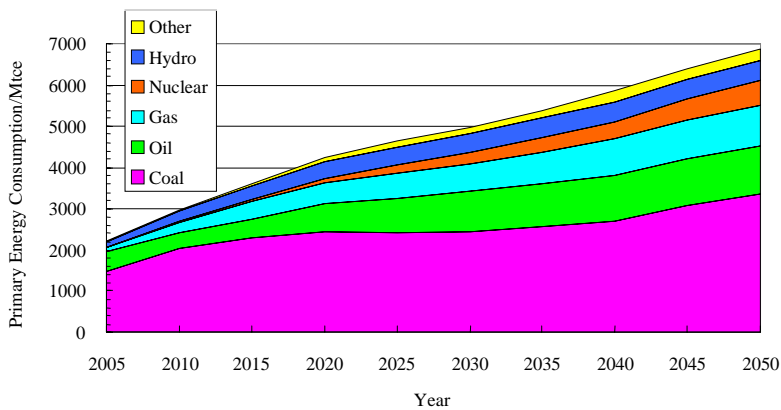
Figure 5 Final energy consumption by sector in the reference scenario



3.2 Primary energy consumption

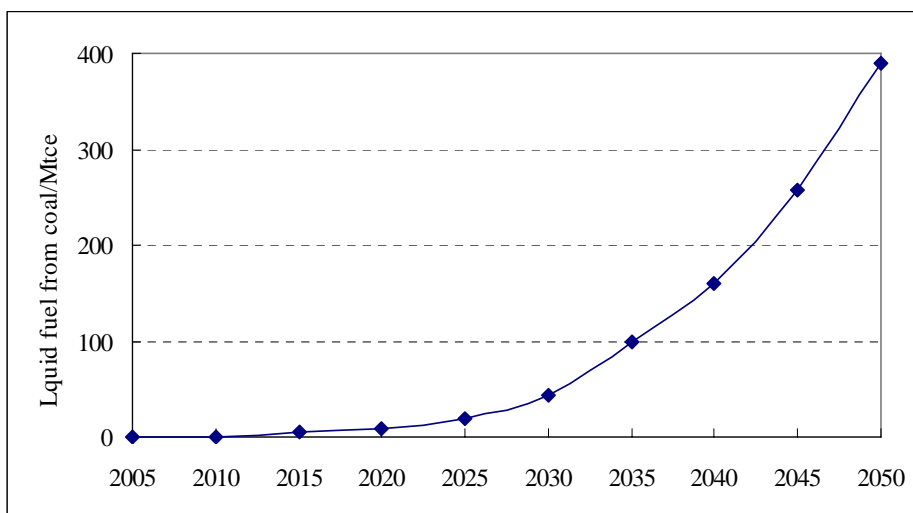
Primary energy consumption is expected to grow by 2.5% per year from 2005 to 2050, reaching 6883Mtce by 2050 with coal, oil, gas, nuclear, hydro, and other new and renewable energy accounting for 48.6%, 17.1%, 14.5%, 8.5%, 7.1% and 4.3%, respectively for the reference case. The percentage of coal is anticipated to drop by 19% between 2005-2050, while that of every other fuel will increase, in particular, by 10% for gas, and by 8% for nuclear.

Figure 6 Primary energy consumption by mix in the reference scenario (Note: Other - Wind, Solar, Geothermal and Biomass)



The model assumes that future oil price would go up steadily to 100US\$/bbl by 2050. In view of limited time available for this work, no sensitivity about this value was tested, future work should explore this. With consideration of coal liquefaction technologies in the model, the modelling shows that liquid fuel from coal is expected to reach 390Mtce by 2050, contributing one third of the conventional oil supply from both domestic mining and imports.

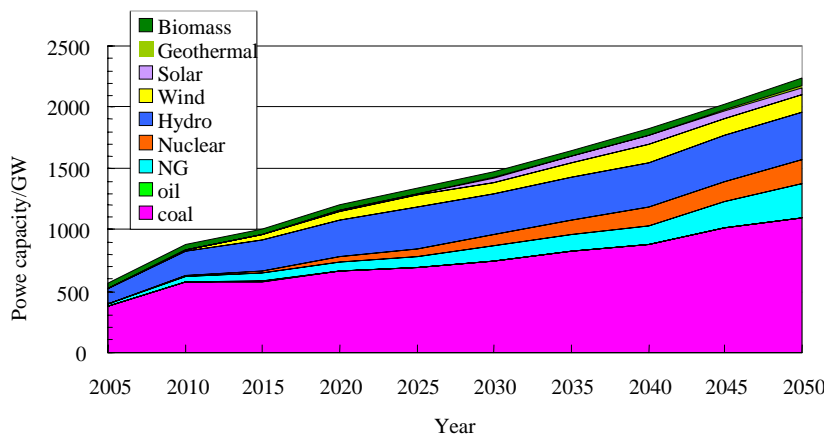
Figure 7 Liquid fuel from coal



3.3 Power generation

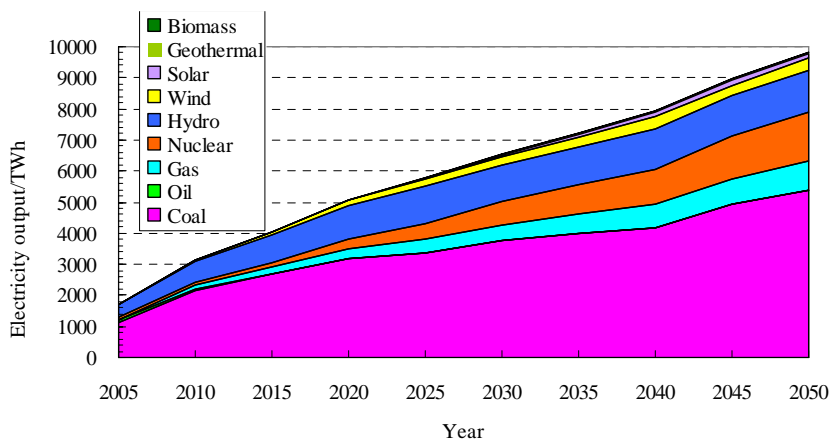
The total capacity of power is expected to grow by 3.3% per year from 2005 to 2050, reaching 2237 GW by 2050 with coal, oil, gas, nuclear, hydro, and other new and renewable energy accounting for 48.8%, 0, 12.8%, 8.9%, 16.9% and 12.5%, respectively, as detailed in Figure 8. Nearly all hydro power resources are expected to be utilized and thus hydro power capacity is expected to be 378GW by 2050. Nuclear and wind is expected to grow to 200GW and 150GW respectively by 2050. The projection for wind deployment used in this study is higher than that used in IEA WEO2008 but lower than some Chinese experts recently predicted. Solar power, biomass power generation and geothermal power are expected to reach 130GW collectively by 2050.

Figure 8 Power capacity and its mix in the reference scenario



Electricity output is expected to increase to 9840TWh by 2050 with annual growth rate of 4% during 2005 to 2050, as displayed in Figure 9. Coal share is expected to decrease to 54.8%, while gas, nuclear, hydro and other renewable is expected to increase to 9.6%, 16%, 13.5%, and 6% respectively. It should be noted that demand in 2008 is below the actual demand (c.3430TWh) in 2008. This is likely to be due to the fact that only the energy service demands for industry and transportation sector were updated for this model.

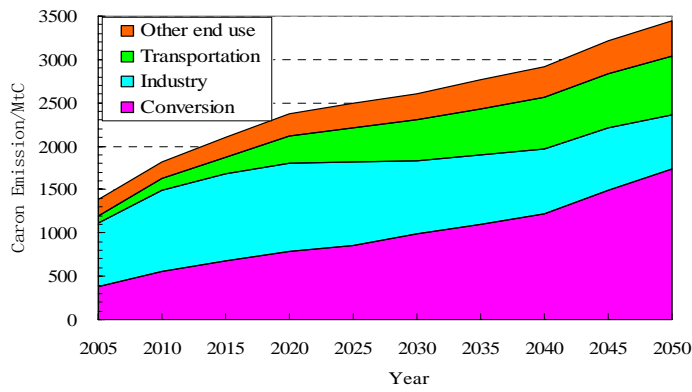
Figure 9 Electricity output and its mix in the reference scenario



3.4 Carbon emissions

Figure 10 shows carbon emissions in the reference scenario. Total carbon emissions are expected to increase to 2377MtC (8.7GtCO₂) in 2020, 2607MtC (9.5GtCO₂) in 2030 and 3441MtC (12.6GtCO₂) in 2050 with annual growth rate of 2% during 2005-2050. By 2050, the share of industry sector in the total emissions is expected to decrease to 18.2%, while the share of conversion and transportation sectors is expected to increase to 50.5% and 19.7% respectively.

Figure 10 Carbon emissions in the reference scenario

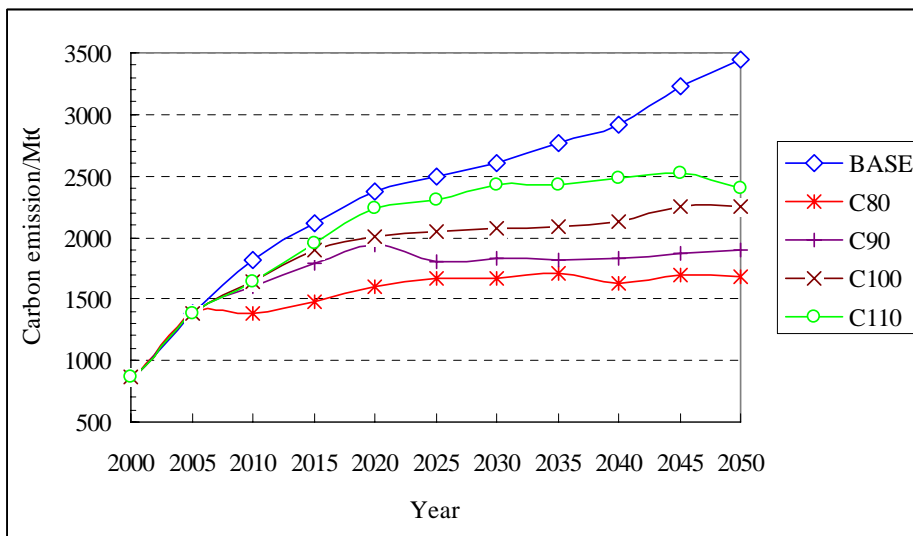


4 Carbon emissions constraint scenarios

4.1 Scenario design

Cumulative carbon emissions during 2005 to 2050 in the reference scenario are 125GtC. Totally four carbon constrain scenarios are designed, namely C110, C100, C90 and C80, in which cumulative carbon emissions during 2005 to 2050 is constrained to 110GtC, 100GtC, 90GtC and 80GtC respectively. The model provides the emissions pathway under all these carbon constraint scenarios, as displayed in Figure 11.

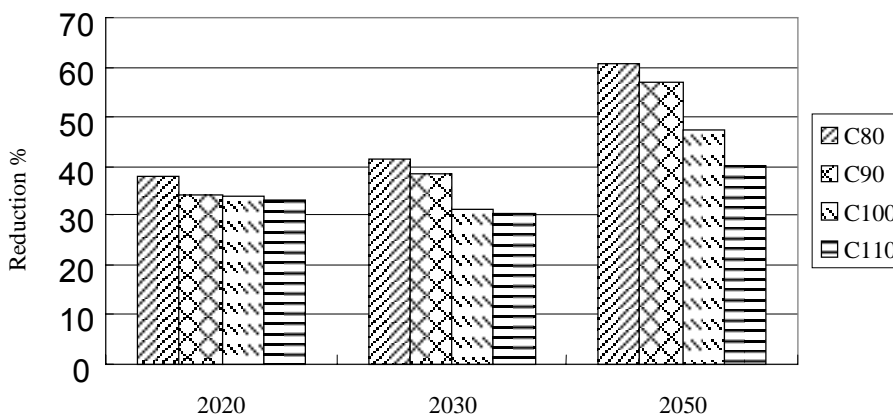
Figure 11 Carbon emissions pathway in different scenarios



Note: BASE = reference scenario

Figure 12 shows carbon reductions relative to the reference for different carbon constrained scenarios. Carbon reductions for 2020 and 2030 are in the range of 30% to 41%, while for 2050 it is in the range of 40% to 61%. A large amount of carbon emissions reductions are required under all these scenarios, in particular, the more stringent scenarios like C80 and C90 in 2050.

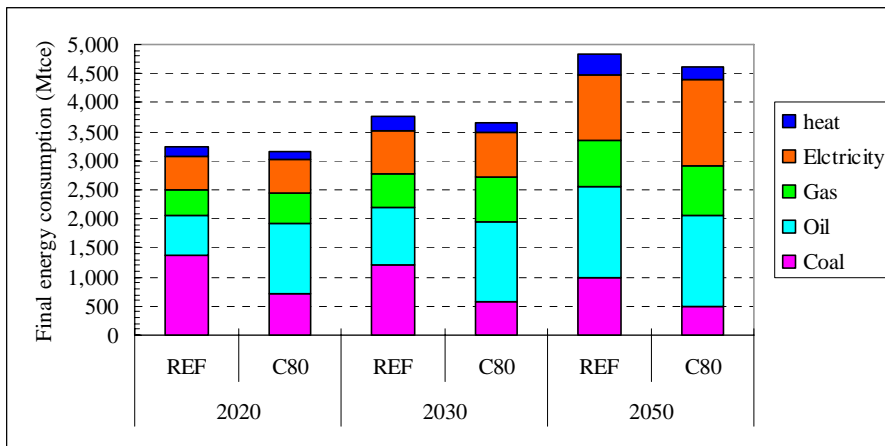
Figure 12 Carbon emissions reduction under different carbon constrained scenarios



4.2 Final energy consumption

Figure 13 compares final energy consumption and its mix between the reference and C80 scenario. Although total final energy consumption would only reduce 2.5-4.4% in C80 compared to the reference scenario, its mix would change significantly. In particular, the share of coal would drop from 21% to 11% while share of electricity would increase from 23% to 32% for the year 2050. Whilst it is recognized that electricity production would still be dominated by coal, here we only focus on final energy consumption. The reason for the reduction in final consumption in C80 in 2050 relative to the reference scenario is due to the greater use of electricity (as this is more efficient at point of use) and the use of more efficient technologies.

Figure 13 Comparisons on final energy consumption and its mix between reference scenario and C80



4.3 Primary energy consumption

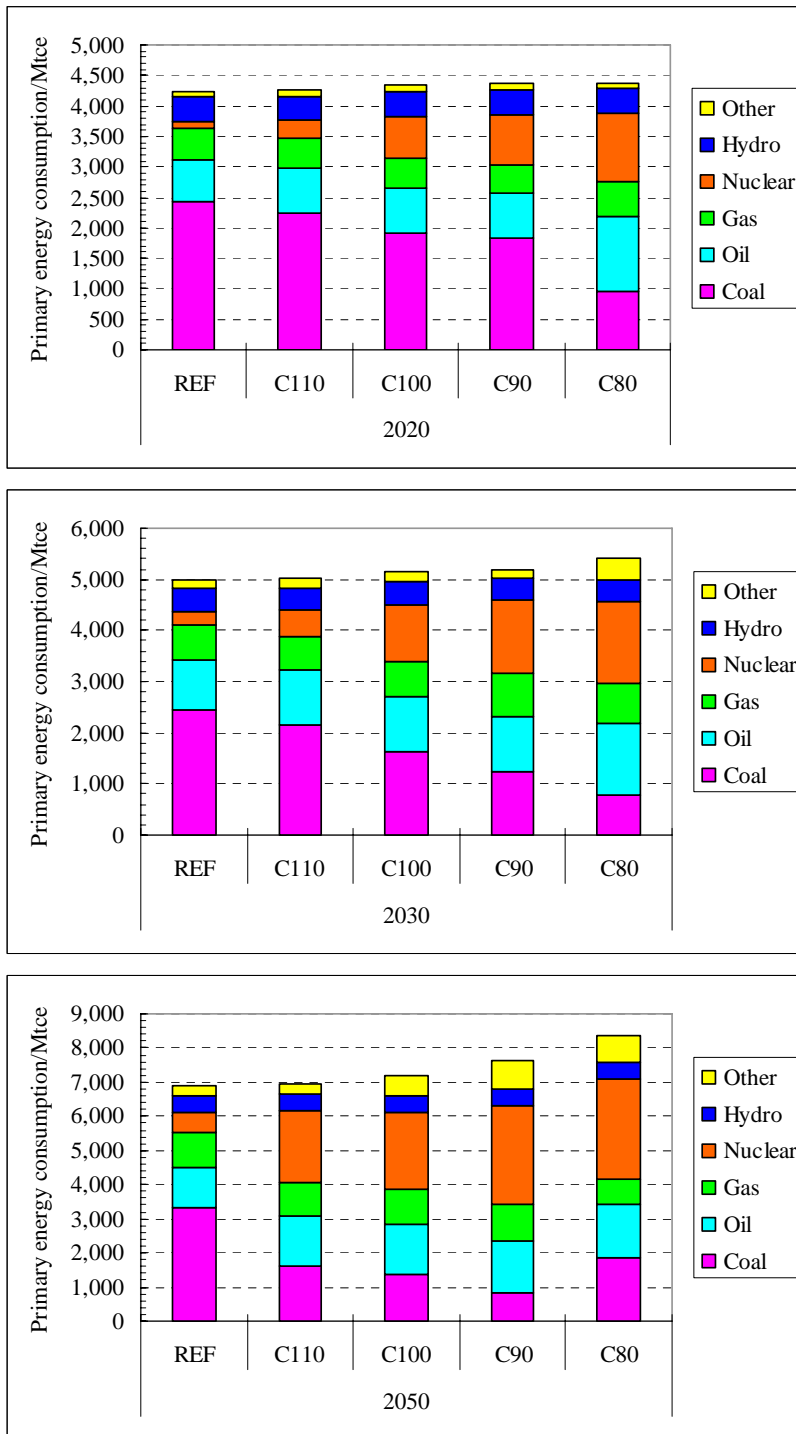
Figure 14 illustrates primary energy consumption and its mix under different carbon constraint scenarios. For the year 2020, coal share is expected to decrease from 57% in the reference scenario to 53%, 44%, 42% and 22% for C110, C100, C90 and C80 respectively, while nuclear is expected to increase from 2.7% to 6.7%, 16%, 19% and 26%. Since almost all hydro has been developed in the reference scenario, the role of hydro power in different carbon constraint scenarios are almost the same as that in the reference scenario. The share of other renewable energy is expected to keep around 2-3% for all scenarios.

For the year 2030, coal share is expected to decrease from 57% in the reference scenario to 49%, 43%, 31% and 14% for C110, C100, C90 and C80 respectively, while nuclear is expected to increase from 5.5% to 10%, 21%, 27% and 29%. Share of other renewable energy is expected to keep around 3%-4% for all scenarios except C80 (7%).

For the year 2050, coal share is expected to decrease from 48% in the reference scenario to 23%, 19%, 11% and 22% for C110, C100, C90 and C80 respectively, while nuclear is expected to increase from 8.5% to 29%, 31%, 38% and 35%. Share of other renewable energy is expected to increase to 8%-16% for the carbon constraint scenarios.

Nuclear and renewable energy such as wind, solar, geothermal and biomass will play a more important role in the more stringent carbon constraint scenarios. For example, nuclear would account for 45% in the total primary energy consumption by 2050 in C80. Reducing emissions sufficiently to achieve the C80 scenario indicates a substantial use would be made of CCS. The cost of SC/USC with capture is lower than nuclear, but investment cost and energy penalty for CCS are another important aspect to determine coal use. CCS technologies are expected to contribute to significant carbon emissions reductions for C80 by 2050. Application of CCS technologies would increase both the coal share and the total primary energy consumption. Thus the coal share increases between the C90 and C80 scenarios.

Figure 14 Comparisons of primary energy consumption and its mix for different scenarios (Note: Other - Wind, Solar, Geothermal and Biomass)



4.4 Power generation

Figure 15 compares power capacity by mix for different scenarios. Total capacity for C80 is higher than the reference scenario, i.e., 4%, 7% and 39% higher for the year 2020, 2030 and 2050 respectively, while electricity output for C80 is 1%, 5% and 37% higher than the reference. There are two main reasons for this. The first is that the stringent carbon reduction target requires a significant change in the final energy consumption mix to increase the share of electricity while reducing the share of coal. For C80, electricity consumption is expected to increase 0.5%, 3.2% and 30% respectively for the year 2020, 2030 and 2050, as detailed in Figure 13. Figure 16 compares all these

numbers. The second is that 466GW of coal-fired power plant with CCS will need to be developed by 2050 in C80 in order to achieve the reduction target. CCS deployment (both in power sector and coal liquefaction) would increase the energy demand for power generation.

Hydro power is a relatively cheap technology to achieve carbon emission reductions. In all scenarios, hydro power is expected to be around 300GW in 2020, 343GW in 2030 and 378GW in 2050. That means almost all hydro resource would be developed firstly to meet future energy demand and carbon constraints.

Wind power is expected to be 250GW and 265GW by 2050 for C90 and C80 respectively. All onshore wind power resource (250GW) is expected to be utilized in C90 and C80.

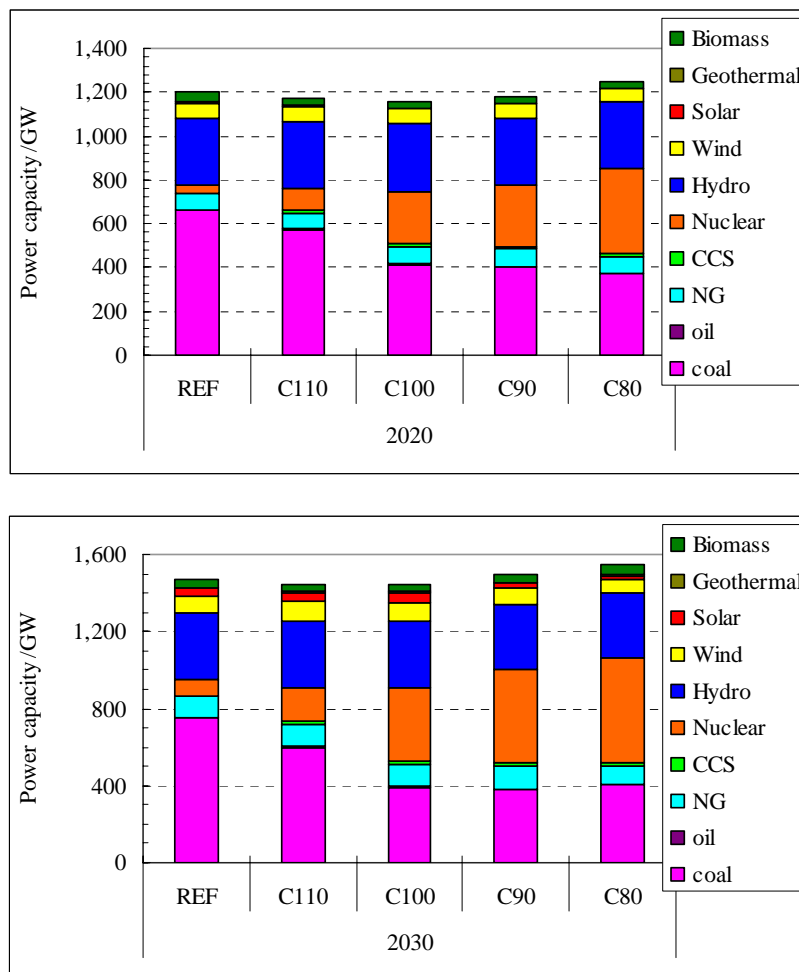
By 2050, the use of other renewable energy including solar, geothermal and biomass is expected to increase from 130GW in the reference scenario, to 170GW, 180GW, 265GW and 390GW for C110, C100, C90 and C80 respectively.

Nuclear power is expected to play a very important role for carbon emissions reduction in the future. By 2050, nuclear power would increase from 200GW in the reference scenario to 710GW and 765GW for C110 and C100 respectively. The model sets a limit of 1000GW of nuclear by 2050. For both C90 and C80, nuclear power would need to expand to 1000GW by 2050. 1000GW would represent a very large step-change in the build rate for nuclear power stations.

Coal-fired power plant with CCS would be less than 15GW during 2020 to 2050 for all carbon constraint scenarios except C80 where it would increase to 466GW in 2050 for C80. In C80 almost all NG is used in the end use sectors instead in power, while less coal is used in the end use sectors and more coal used in power sector (see Figure 15 for details).

By 2050, coal-fired power plants with CCS, nuclear power and renewable energy would account for 15%, 32% and 33% respectively in the total power capacity.

Figure 15 Comparisons of power capacity and its mix for different scenarios



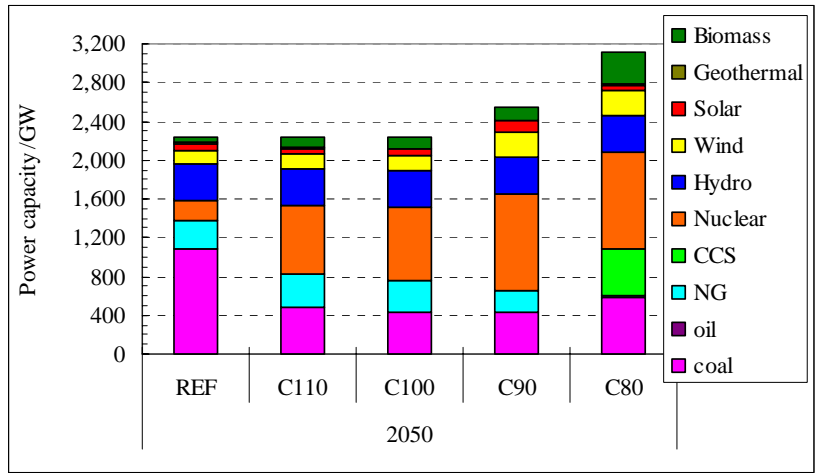
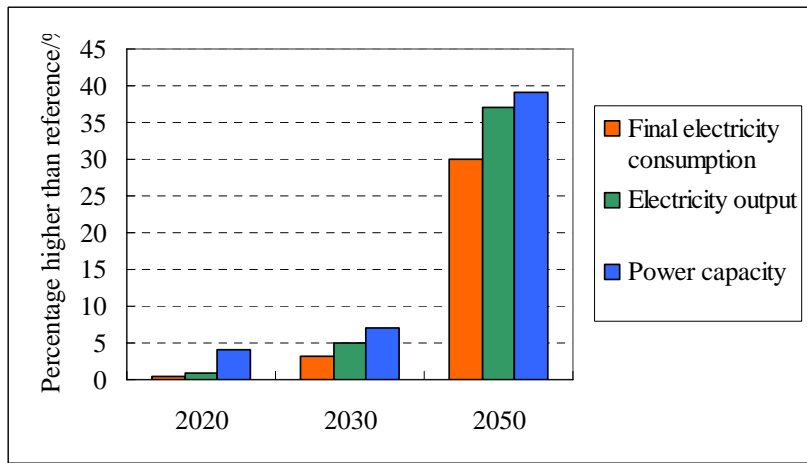


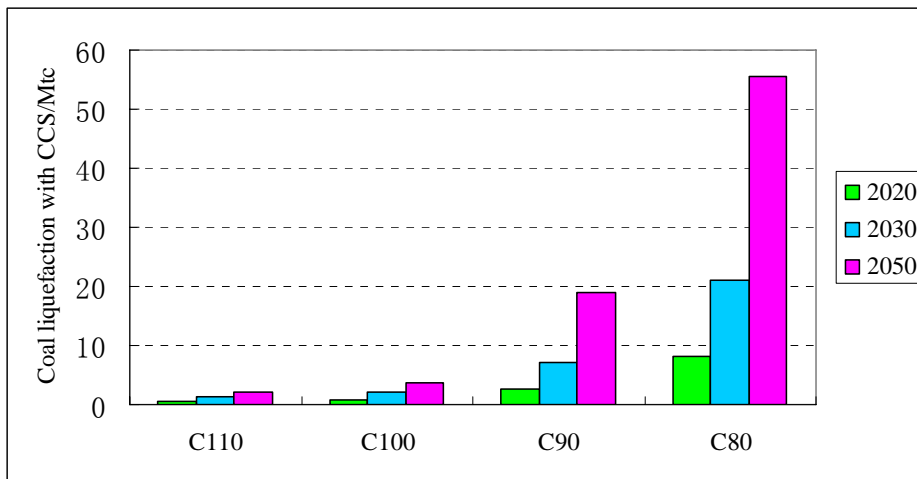
Figure 16 Comparison of electricity consumption and output between C80 and reference



4.5 Coal liquefaction with CCS

Figure 17 shows liquid fuel produced from coal liquefaction with CCS would increase to 55Mtce by 2050 in C80. Comparing Figure 17 with Figure 7, we can see that coal liquefaction in the reference is much higher than in the carbon constraint scenarios. For all scenarios, carbon constraints are set for total emissions instead of for the power sector only. The increased emissions of the liquefaction plants has an effect on the emissions allowed, thus coal liquefaction drops significantly from the reference scenarios and all coal liquefaction is with CCS in the constraint scenarios. But compared with CCS in the power sector, coal liquefaction with CCS in C80 (56Mtce in 2050) only accounts for a small proportion of the total storage capacity.

Figure 17 Liquid fuel produced from coal liquefaction with CCS

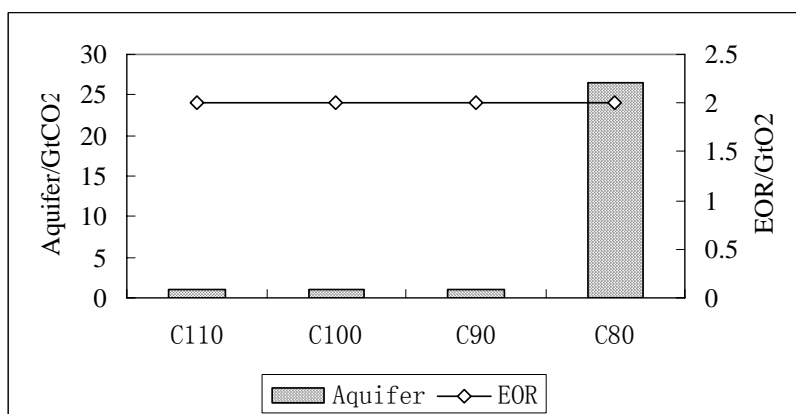


4.6 Carbon Sequestration

China’s proved recoverable reserves for oil are around 2200 million tonnes. If oil and CO₂ contact percentage is assumed as 75%, the extraction rate for CO₂ enhanced oil recovery (EOR) as 5.3%, and 2.5 tonnes CO₂ needed to produce 1 tonne oil, then total CO₂ EOR storage capacity potential could be estimated as 2 GtCO₂ and CO₂ EOR potential as 800Mt. For oil fields with different API⁵ value, extraction rate for CO₂ EOR is in the range 5.3% to 18.3%. Considering not all oil fields are suitable for EOR and some small oil fields are suitable but their storage capacity might not be able to host at least 10 years worth of emissions, we use 2 GtCO₂ EOR storage capacity potential and 800Mt CO₂ enhanced oil recovery potential in the model.

CO₂ EOR provides additional revenue from enhanced oil production. Therefore, for all carbon constraint scenarios, all the available CO₂ EOR potential is assumed to be used to store the CO₂ captured from both the power sector and coal liquefaction. This equates to 2 GtCO₂, as shown in Figure 18. For C80, an additional 26 GtCO₂ will need to be sequestered in aquifers since EOR is not able to provide enough capacity for the total CO₂ captured.

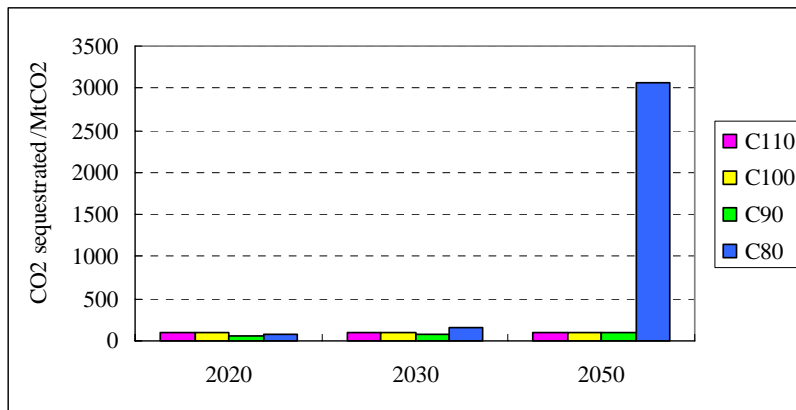
Figure 18 Total CO₂ sequestered during 2005 to 2050 in different scenarios



From Figure 19, it can be seen that total CO₂ sequestration per year is expected to grow considerably for C80 by 2050 (3000MtCO₂) (this number includes aquifer storage).

⁵ American Petroleum Institute

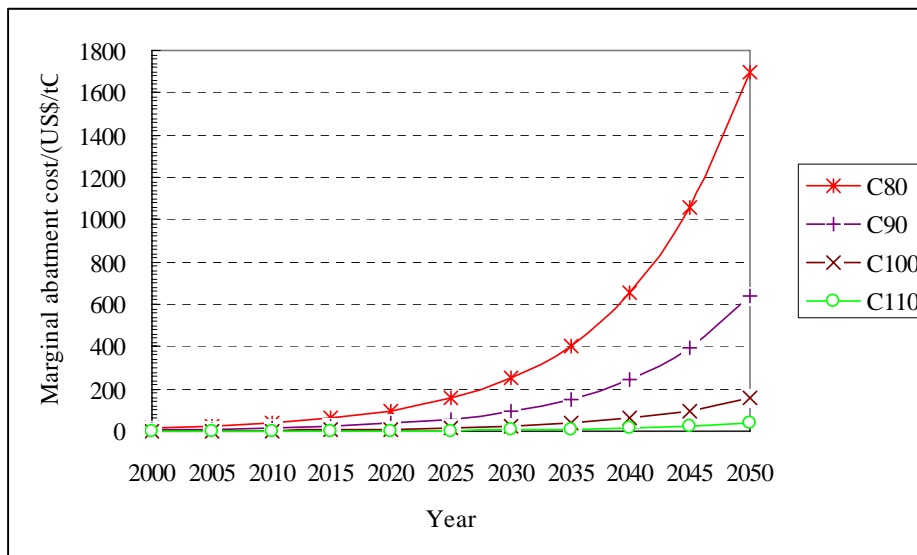
Figure 19 Annual CO₂ sequestrated in different scenarios



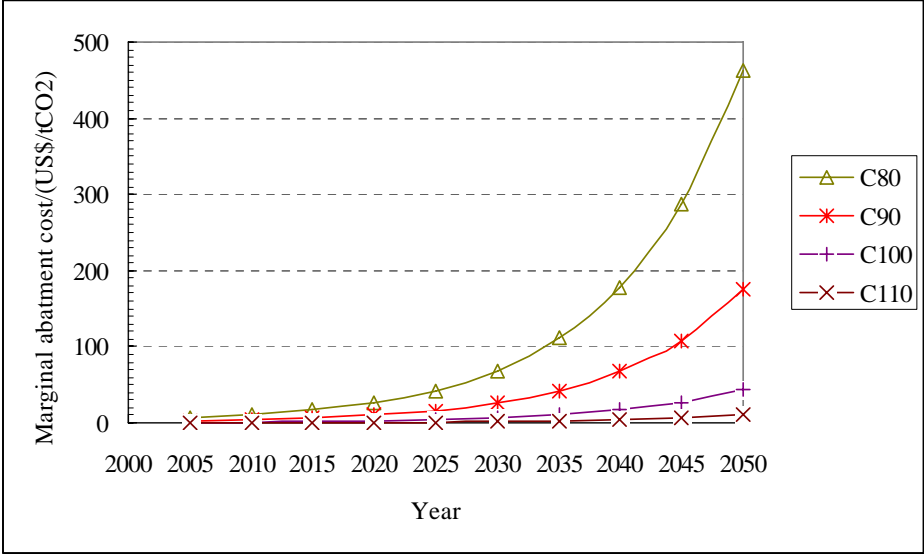
4.7 Marginal abatement cost

Marginal abatement cost is another reflection of the solution of the model when a carbon emissions constraint is introduced. It is not the average abatement cost, instead it is the cost when one more tonne of carbon is needed to be further reduced. Figure 20 displays marginal abatement cost for different scenarios. With 50US\$/C (14US\$/tCO₂), it is possible to constrain carbon emissions by 2050 at twice the 2005 level (C110). To cut the carbon emissions by 2050 at 1.7 and 1.4 times the 2005 level, marginal abatement cost would go up to 160US\$/tC (44 US\$/tCO₂) and 630 US\$/tC (172 US\$/tCO₂) respectively. For C80, reduction requirement for 2050 is higher, so the marginal abatement cost would rise to 1700US\$/tC (463 US\$/tCO₂). A high value of the marginal abatement cost such as 463 US\$/tCO₂ means that the reduction target would be very difficult to achieve.

Figure 20 Marginal carbon mitigation cost in different scenarios



(a) Cost unit: US\$/tC



(b) Cost unit: US\$/tCO₂

5 Concluding remarks

As a developing country with a coal dominated energy mix, China faces severe challenges when coping with climate change. With the accelerated urbanization and industrialization that comes with economic development and living standard improvement, China's carbon emissions are expected to continue to grow to 12.6GtCO₂ by 2050. But owing to China's continued effort on energy efficiency improvement and development of new and renewable energy, the annual growth rate of carbon emissions is expected to drop significantly from 5.7% during 2000-2005 to 2% during 2005-2050.

The modelling in this study considers a lot of advanced technologies both in the energy supply and demand sides. The availability of these technologies significantly reduces carbon emissions in the reference scenario, as well as the abatement costs. Policies and programs that encourage the development, demonstration and commercialization of advanced energy technologies are needed.

Due to China's coal-dominated energy resource characteristic and limited renewable energy resource, carbon emission reductions will rely heavily on the development of nuclear power, in particular if more stringent reductions are required. For example, 1000GW of nuclear would be needed for C80 and C90 scenarios. Such large scale of nuclear power development will be challenged by constraint factors like site selection, public acceptance, investment, safety and waste disposal. CCS technologies would provide another solution for future carbon emissions abatement, in particular, for the more stringent reduction targets. More than 400GW coal-fired power plants with CCS by 2050 would be required to achieve the C80 reduction. More stringent carbon reduction targets would rely on more CCS technologies.

In the near term enhanced oil recovery with CCS is a cost-effective option and in total 2GtCO₂ could be sequestered to produce 800Mt of oil in the whole time horizon for all carbon constraint scenarios. For C80, an additional 26GtCO₂ would need to be sequestered in aquifers as EOR storage space would have been used.

Modelling results of marginal abatement cost show that with 50US\$/tC it is possible to control carbon emissions by 2050 at twice the 2005 emissions level. To cut the carbon emissions by 2050 to only 1.7 times of 2005 level, the marginal abatement cost would go up to 160US\$/tC. The marginal abatement cost would rise significantly if carbon emissions needed to be further cut.

MARKAL is an optimization model which seeks the least-cost options to meet user defined demands and carbon constraints. The marginal abatement cost obtained from the model used in this study is the lowest one for each carbon constraint scenario. The use of CCS would absolutely reduce the marginal abatement cost under a defined scenario if CCS is selected to meet part of the carbon reduction requirements. However the increased marginal abatement between the less stringent carbon constraint scenarios to more stringent carbon constraint scenarios is caused by the reduction requirement increase, not by an increased use of CCS. Moreover, the marginal abatement cost obtained from the model is for the whole energy system not for a specific technology (e.g. CCS). As such, the marginal abatement cost cannot be directly compared with the abatement cost for a specific technology including CCS.

The investment cost for nuclear power, offshore wind power, PV, SC/USC with capture and IGCC with capture are assumed as 1500US\$/KW, 1500US\$/KW, 2000US\$/KW, 1100US\$/KW and 1300US\$/KW by 2050 respectively. The energy penalty for capture is assumed as 10% for SC/USC and 8% for IGCC respectively. Further reduction in the investment cost for these key carbon abatement technologies and reduction in the energy penalty for CCS is crucial to reducing the marginal abatement cost. Cooperation between developed and developing countries as well as financial and technology transfer from developed to developing countries should be encouraged to further research, develop and demonstrate these advanced technologies including CCS.

In the near term, as announced by Chinese government, the priority for China's energy development is still energy conservation and development of new and renewable energy. But CCS offers an important strategy option for future carbon mitigation if CO₂ concentration in the atmosphere has to be stabilized at 550ppmv_{eq} or even lower. Two significant obstacles for CCS development exist, one is its relatively high investment cost, another is the energy penalty, which would put higher pressure on coal supply. It is very important to demonstrate CCS through international cooperation to overcome these obstacles.

6 Recommendation for future work

In this project, energy service demand is only updated for industry and transportation sector. Other sectors will also need to be updated in future MARKAL modelling work to gain a more complete picture of China's project energy service demand.

Modelling results are highly dependant on the available technologies, in particular, availability of advanced technologies, as well as the characteristics (cost, efficiency, etc.) of the technologies. More research on the cost and efficiency of advance technologies both on supply and demand sides are needed to further update the model. For example, NGCC with CO₂ capture is not currently included as a technology option within China MARKAL. This should be addressed as a priority for future modelling work.

Due to time constraints, the sensitivity of the results to oil price was not explored during this work. Future studies could look at the sensitivity of the results to oil price.

Marginal abatement costs obtained from the model is for the whole energy system not for a specific technology (e.g. CCS). How much technology costs needs to be lowered to reduce marginal abatement cost to a certain level requires further investigation.

Carbon emission reductions could be achieved not only from a changed fuel and technology mix, but also from a reduction of energy service demand. But in the standard MARKAL used in this study, emission reductions could only be achieved by changing the fuel and technology mix since energy service demand is an input of the model. Another version of the model, MARKAL-ED, by introducing price and income elasticity for each energy service demand, is able to overcome this disadvantage. The crucial issue is how to identify the proper elasticity for each energy service demand.

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