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AVOID – providing key advice to the UK Government on avoiding dangerous climate change

AVOID – Avoiding dangerous climate change

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Key outcomes / non-technical summary

This study assesses the potential for China to significantly reduce its carbon dioxide (CO_2) emissions to 2050, with a focus on CO_2 from energy and industrial emissions. The study uses modelling by the International Institute for Applied Systems Analysis (IIASA) and Imperial College London, to undertake a detailed analysis of the key technologies that could be deployed in China as part of a low carbon transition. The study also assesses the challenges and opportunities, in terms of a range of factors including R&D requirements, costs and use of resources, facing China and the international community in achieving such a transition.

Key outcomes are that there are feasible pathways for China to significantly decarbonise its economy by 2050, using a range of commercial and pre-commercial technologies, and that decarbonisation of the electricity sector and energy efficiency across all of the major energy-using sectors (transport, buildings and industry) will be critical. Many important technologies (including a range of electricity generation technologies such as solar, wind and carbon capture and storage) are only likely to be deployed with specific technology support including some form of long-term, stable carbon price. In addition, energy efficiency measures will require careful and effective regulatory and enforcement mechanisms. Thus, experience from the international community in developing trading schemes and regulatory and monitoring mechanisms could be highly beneficial.

The challenges and opportunities of a low carbon pathway should be set in the context of a business-as-usual pathway for China, which presents a range of challenges of its own, resulting from a likely continued reliance on coal and oil.

Potential for any media interest

Following the 2009 Copenhagen and 2010 Cancun UN Framework Convention on Climate Change (UNFCCC) summits, there has been increasing media interest in the greenhouse gas emissions from China and other major emerging economies. In addition, recent (unpublished as at June 2011) analysis from the International Energy Agency (IEA) suggests that following the global economic downturn of 2008 and 2009, greenhouse gas emissions have rebounded very strongly, to such an extent that the global target of achieving a 2^O Celsius limit to global warming is becoming increasingly unlikely. There is therefore potential for media interest into this study which assesses pathways for China to a 2050 level of emissions which – in conjunction with a significant global decarbonisation effort - is broadly feasible with a global 2^O Celsius limit to global warming.

Contents

Study objectives and methodology

This study by the Grantham Institute for Climate Change, Imperial College London, assesses the potential for China to significantly reduce its carbon dioxide (CO_2) emissions to 2050, with a focus on CO_2 from energy and industrial emissions[1]. The work has been undertaken as part of the AVOID research programme into avoiding dangerous climate change[2], which is funded by the UK Government's Department of Energy and Climate Change (DECC), and Department for Environment, Food and Rural Affairs (DEFRA). However, this work reflects the analysis and views of the authors rather than the UK Government.

The study uses the International Institute for Applied Systems Analysis (IIASA) MESSAGE energy technology model to project the CO_2 emissions trajectories in China which would form part of a global least-cost GHG emissions trajectory that limits global warming to 2 degrees Celsius above pre-industrial levels. The model provides a detailed analysis of the energy supply system (including electricity generation, fossil fuel extraction and conversion processes) for given levels of energy demand (split into electric and non-electric demand) in the major end-use sectors of the economy (industry, transport, residential and commercial buildings). Imperial College's analysis is focused on:

- analysing the implications of the low-carbon electricity generation mix in the MESSAGE model, by considering the various challenges to commercialising and scaling up the different low-carbon generation technologies;
- assessing what contribution a range of commercial and pre-commercial CO_2 mitigation technologies and measures could make to achieving the energy demand levels implied for each major end-use sector (industry, transport, buildings) in IIASA's low-carbon scenarios, based on specific models of the transport, industry and buildings sectors developed by Imperial College analysts;
- assessing the implications of these different mitigation technologies and measures on China and the international community, including the challenges to develop and deploy them, their costs, their material resource usage, and the opportunities they provide for international collaboration;
- considering the impacts of the low-carbon emissions trajectories on China's overall energy system, including its demand for fossil and non-fossil fuels, its use of land and water resources, and its energy network and infrastructure requirements.

Where relevant this study has been compared to the following recent studies on China:

- IEA BLUE Map projection in Energy Technology Perspectives 2010 [1];
- Low-Carbon Economy Scenario Studies performed by the Energy Research Institute in China [2];
- AIM modelling done for the AVOID programme.

[1] Non-CO_2 greenhouse gas (GHG) emissions and CO_2 emissions from land use are not explicitly analysed. In the IIASA modelling used in this study, sinks from land use change in the Central and Planned Asia (CPA) region increase from approximately 13MtCO_2/year in 2010 to 200-400MtCO_2/year by 2050 in the low-carbon scenarios. CO_2 emissions from energy and industry in the low-carbon scenarios are about 12,000-14,000MtCO_2/year less than the Baseline scenario by 2050. So land-use change could be a small but nevertheless significant part of overall CO_2 abatement by 2050.

[2] Details of the AVOID programme are available at: http://ensembles-eu.metoffice.com/avoid/

Project team and acknowledgements

This study was led by the Grantham Institute for Climate Change at Imperial College London, with detailed analytical input from the International Institute of Applied Systems Analysis (IIASA).

The Grantham Institute project team was led by Ajay Gambhir, Research Fellow on Mitigation Technology, under the supervision of the project owner Neil Hirst, Senior Research Fellow. The core Grantham team consisted of Dr Tamaryn Brown, Mitigation Research Associate, and a team of postgraduate (PhD) students investigating a range of low-carbon technologies – Mark Faist, Sam Foster, Mark Jennings, Luis Munuera, Danlu Tong, and Lawrence K C Tse.

The IIASA input was provided by Dr Niels Schulz, Research Fellow on the IIASA Global Energy Assessment, and Professor Keywan Riahi, Acting Programme Leader for the Energy Programme at IIASA.

The analysis was overseen by a technical expert panel of senior academics at Imperial College, consisting of: Professor Nilay Shah (energy systems and cross-cutting issues); Professor Jenny Nelson (power generation – solar); Professor Robin Grimes (power generation – nuclear); Dr Tim Cockerill (power generation – wind); Dr Paul Fennell (power generation – CCS, and industry); Professor David Fisk (buildings); Dr James Keirstead (urbanisation); and Dr Ricardo Martinez-Botas (transport).

The analysis was reviewed by Dr Pei Liu, Assistant Professor at the BP Clean Energy Research and Education Centre at Tsinghua University in Beijing.

The team would like to thank the following for their invaluable input during the project: Dr Simon Buckle, Dr David Howey, Dr Ned Ekins-Dawkes, Jimmy Liu and Simon Middleburgh of Imperial College London; Michael Taylor, Cecilia Tam, Dr Peter Taylor and Jonathan Sinton of the IEA; Antony Froggatt of Chatham House; Dr Ken'ichi Matsumoto of the University of Shiga Prefecture; Dr Andrew Minchener, freelance consultant formerly of the IEA Clean Coal Centre; Dr Lee Schipper of UC Berkeley; Professor Nick Jenkins of Cardiff University; Professor Yangjun Zhang of Tsinghua University; Professor Shigeki Kobayashi of Toyota Central R&D Laboratories; and Professor Diana Urge-Vorsatz of the Central European University.

Executive Summary

1. The future course of China’s CO_2 emissions is of critical importance for climate change mitigation. These emissions have more than doubled since 2000 and, on business as usual assumptions, could represent nearly 30% of global emissions by 2050. This reflects China’s status as the most populous nation on earth with a rapidly developing (largely coal-based) economy. As for other countries, climate change mitigation is only one of the objectives of China’s energy policy. In addition to China’s economic development objectives, energy security is a growing concern for China as its oil imports increase, and the health impacts of local air pollution remain a key political and economic issue.

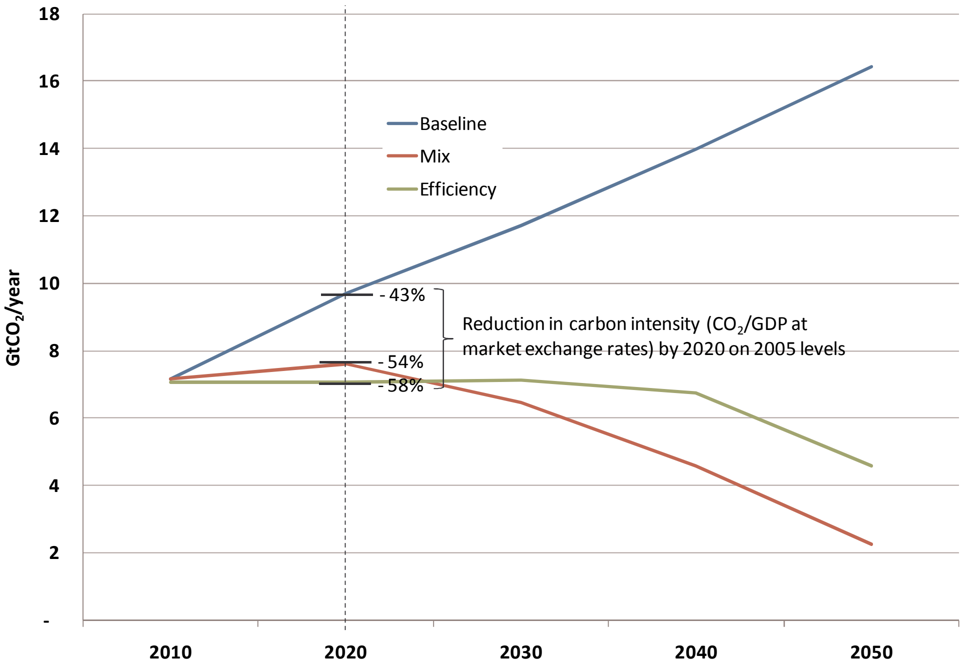
2. In this study we examine the pathways through which China could reduce energy related CO_2 emissions by 2050, to levels that would be broadly consistent with the global 2^o Celsius objective. We review the technologies that would be required, the barriers to their deployment, and the wider implications for China’s energy policy and for the rest of the world.

3. The framework for the study is provided by three scenarios of the International Institute for Applied Systems Analysis (IIASA) for its forthcoming Global Energy Assessment report, which focus on the Central and Planned Asia (CPA) region, approximately 90% of which is China in population and GDP terms. The study also uses original analysis by the Grantham Institute, drawing on the technical expertise of Imperial College. We have also compared IIASA’s results, and our own, with the results of other published studies, notably by the International Energy Agency and China’s Energy Research Institute (ERI).

4. The IIASA scenarios are: a Baseline Scenario with no emissions limit; a “Mix” abatement scenario in which a wide range of low carbon energy technologies is employed; and an “Efficiency” scenario with a greater emphasis on energy demand reduction, as well as a higher emissions level by 2050, implying greater effort thereafter to achieve the 2^o Celsius objective.

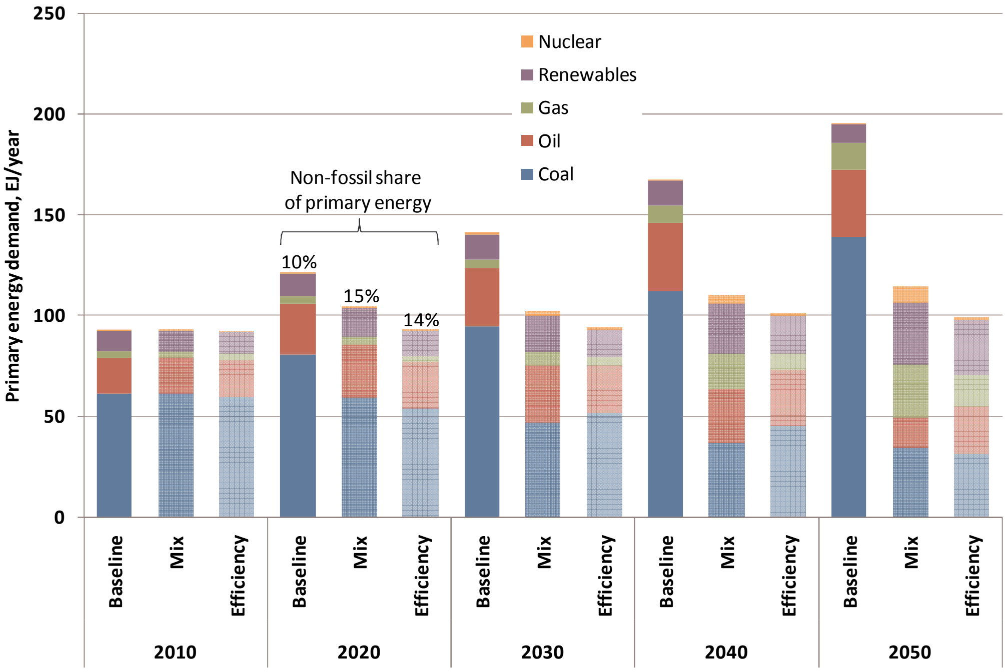
5. Figure ES1 illustrates these three scenarios. In the Baseline scenario the CPA region’s energy-related CO_2 emissions reach 16GtCO_2 by 2050, compared to 4.5 GtCO_2 in the Efficiency scenario and 2.2 GtCO_2 in the Mix scenario. The Baseline scenario implies carbon intensity reductions of 43% by 2020 on 2005 levels, sufficient to come within the target range of China’s Copenhagen Accord pledge of a 40-45% reduction in carbon intensity by 2020 on 2005 levels. The Mix and Efficiency scenarios imply significantly more rapid reductions in carbon intensity. In other words, China’s stated ambitions for carbon reductions to 2020 appear more consistent with the Baseline than with the abatement scenarios. This does not alter the message of the Mix and Efficiency scenarios that dramatic reductions in CO_2 emissions are achievable over the longer term. But it underlines the need for early action if these reductions are to be achieved. Imperial’s own modelling, described in detail in this report, suggests that provided key low-carbon technologies penetrate through the different sectors of the Chinese economy, the rates of emissions reductions to 2050 suggested by the Mix scenario are feasible.

Figure ES1: Energy CO_2 emissions trajectory for Central and Planned Asia (CPA) region to 2050



6. Figure ES2 shows the primary energy demand projections to 2050 for the CPA region. By 2020, non-fossil sources would make up 10% of total primary energy in the Baseline scenario, compared to 15% in the Mix and 14% in the Efficiency scenarios. These can be compared to China's Copenhagen Accord pledge to source 15% of primary energy from non-fossil sources by 2020.

Figure ES2: Primary Energy Demand in the IIASA Baseline and abatement scenarios for CPA



7. In the IIASA Baseline scenario, by 2050 coal continues to supply more than 2/3 of primary energy, as it does today, whilst remaining the largest source of energy for power and industry and also contributing about half of China's oil supply through coal-to-liquids (CtL) conversion technologies. The scenario implies a more-than-doubling of China's coal production, already by far the largest in the world at over 2 billion tonnes per year. However the feasibility of increasing production on this scale can be questioned not only on environmental grounds but also in relation to accessible coal reserves. China's largest coal reserves are in Xinjiang Province in the Far West, thousands of miles from major centres of demand. CtL technology, which is being developed in China, may be desirable on grounds of energy security, to moderate the growth of China's oil imports, but without abatement measures it is very carbon-intensive. In addition, water shortage is a growing problem in many parts of China and CtL is an extremely water intensive technology, which could limit the scale of its deployment.

8. The IIASA Mix abatement scenario is treated as a "central case" in this study, as it is more pessimistic on the degree of energy efficiency improvements and achieves a lower emissions level by 2050, compared to the Efficiency scenario, thereby requiring a deeper penetration of low-carbon technologies. In the Mix scenario, primary energy demand is reduced by about 40% compared to the Baseline scenario by 2050. Coal and gas with CCS, renewables, and nuclear power, together almost entirely displace unabated coal from electricity generation. Oil demand is less than half the level in the Baseline scenario, as a result of greater vehicle efficiency, increased use of biofuels, and the deployment of electric and hybrid vehicles. Low carbon electricity increases its penetration in the industry and building heating sectors. CO_2 emissions from energy conversion (including CtL), by which primary energy is converted to usable forms for the industry, transport and buildings sectors, is largely abated with CCS.

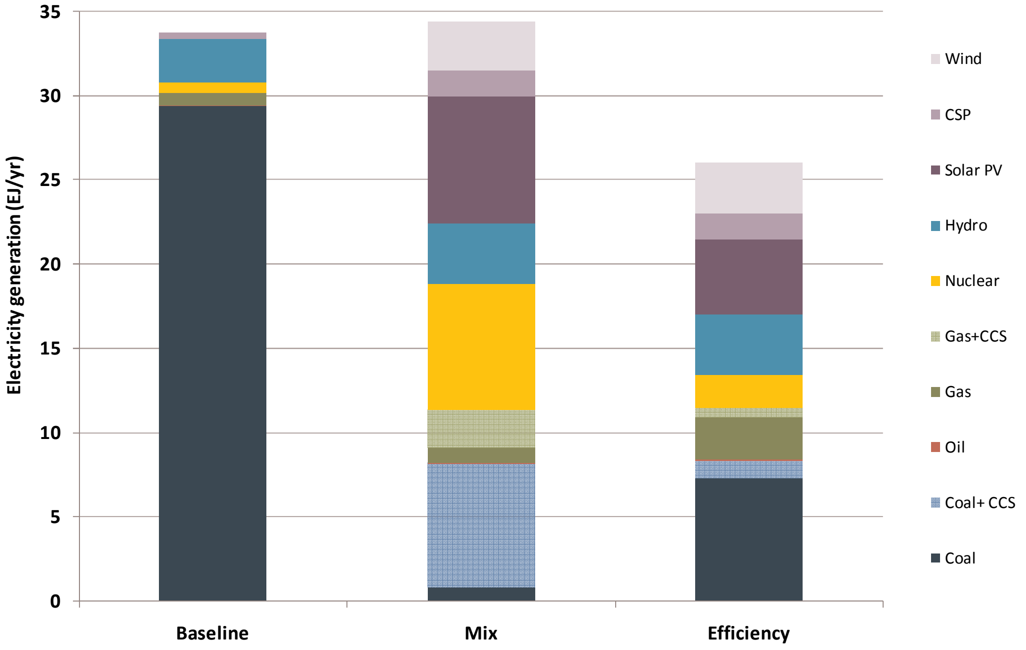
9. Besides achieving much lower CO_2 emissions, the Mix abatement scenario has significant advantages for local environmental pollution and energy security. Oil imports are reduced by about 20% compared to the Baseline scenario by 2050. Sulphur dioxide (SO_2) and particulate matter (PM2.5) emissions (two of the most damaging local pollutants to health) are less than half the Baseline scenario level by 2050.

10. Compared to the Baseline scenario, the projected loss to consumption by 2050 in the Mix scenario is 2% of GDP for the CPA region. This is in the context of a projected increase in overall consumption growth of 500% over the same period, and is the cost of abatement in the CPA region, which may not necessarily be the cost borne by that region, for example as a result of international carbon trading.

POWER GENERATION SECTOR

11. Figure ES3 shows the total electricity generation, split by generation technology, in the three IIASA scenarios. Total generation in the IIASA Mix scenario in 2050 is not very different from the Baseline, as the increased penetration of electricity into the industry, buildings, and transport sectors roughly balances the reduction in overall energy demand due to greater energy efficiency. However the sources of power are very different as solar PV, wind, nuclear power, and coal and gas with CCS almost entirely displace unabated coal.

Figure ES3: Electricity generation in 2050 in the IIASA Baseline and abatement scenarios in CPA



12. The contribution of solar PV in the IIASA MIX scenario is much larger than in other studies, reflecting IIASA's relatively optimistic estimate about its future cost. Imperial College's analysis suggests there could be barriers to the continued cost reductions of solar PV, which could mean that nuclear and hydro would need to play a larger role. This is feasible considering China's large hydro resource and other studies' more optimistic projections of nuclear by 2050.

13. There will be a number of challenges involved in scaling up each of the major low-carbon power generation technologies in the abatement scenarios. Continued investment in R&D to bring down the costs of solar PV and to commercialise CCS will be critical factors to achieving the large penetrations of these technologies. Continued support for wind power will also be essential to ensure its deployment. Nuclear could also be a key technology, requiring careful consideration of access to uranium supplies, through either more efficient fast-breeder reactors or alternative (thorium) fuel reactors. And the changing climate and its effect on rainfall and water availability will be key considerations for a number of electricity generation technologies, especially hydro power.

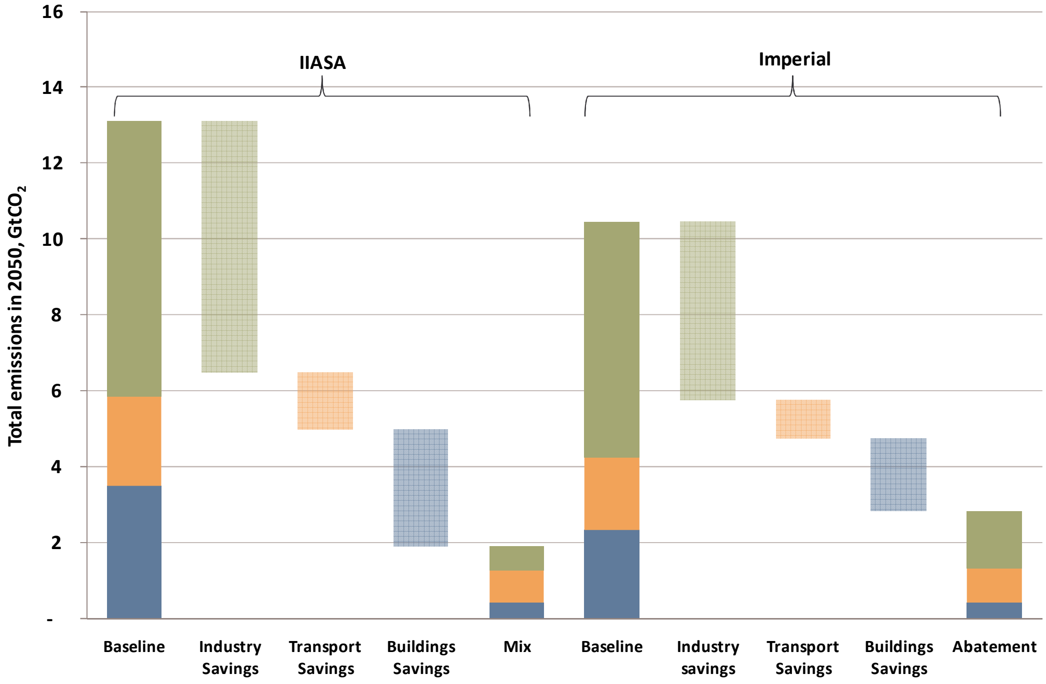
14. In addition, one of the greatest challenges in providing decarbonised electricity will be in balancing the system to ensure that supply meets demand, as more responsive generation plant such as coal-fired plant (whose output can be varied relatively quickly in response to demand variation) is replaced by variable output renewables (wind, solar), or nuclear which is currently best suited to base load generation. China's wind, solar, and hydro resources are highly dispersed geographically, and the development of a strong long distance grid will be essential to exploit them fully.

EMISSIONS REDUCTIONS IN THE INDUSTRY, TRANSPORT AND BUILDINGS SECTORS

15. The IIASA scenarios provide a detailed description of the development of energy supply technologies (power generation, energy production, refining and conversion technologies) but do not specify the demand-side technologies that would deliver the projected energy demands (by fuel type) within the industry, transport and buildings sectors. Hence Imperial has developed a set of detailed models for these sectors, to assess what technologies would in combination achieve the magnitude of emissions savings in the IIASA Mix scenario.

16. In the Imperial abatement scenario, the total emissions savings for the three end-use sectors, including the indirect emissions savings resulting from decarbonisation of the electricity sector, are 7.6 $GtCO_2$ by 2050, compared to a baseline level of 10.4 $GtCO_2$, resulting in emissions of 2.8 $GtCO_2$. This is broadly comparable to the IIASA analysis, as shown in Figure ES4. A key difference is that the IIASA Baseline is higher than the Imperial Baseline, as a greater level of business as usual energy efficiency improvement is projected by Imperial. This underlines the importance of linking projected emissions savings to a particular Baseline scenario. Another difference is that the Imperial analysis is for China alone, rather than the (approximately 10% larger) CPA region.

Figure ES4: Comparison of emissions savings in Imperial and IIASA abatement scenarios by 2050



Notes: Emissions do not include energy conversion emissions, which are 2.8 $GtCO_2$ in the IIASA Baseline and 0.4 $GtCO_2$ in the IIASA Mix scenario by 2050. Imperial analysis does not consider the energy conversion sector.

17. Table ES1 outlines the major abatement options in each of the end-use sectors, including the likely abatement cost and key challenges that China might face in achieving the scale-up of the technologies required to achieve the level of abatement indicated.

Table ES1: Emissions savings in the demand sectors, according to the Grantham Institute analysis

		Technology	**2050 abatement (GtCO$_2$)**	**Abatement cost range**	**Key challenges to scale-up to 2050 levels**
Industry		Best available technology (BAT) and energy efficiency	0.71	Negative to Low	• The potential for more savings through closure of plants is limited; • Local iron ore and bauxite is poor quality, which limits efficiency improvements; whilst high quality coal for coking will compete with other uses (e.g. in electricity generation).
		Switching to decarbonised electricity	3.10	Medium	• Emissions savings dependent on decarbonising electricity supply; • Scrap availability is a key limitation for transitioning steel production to electric arc furnace method; • Uptake of biomass depends on a distribution network – relies on geographical proximity of fuel sources to manufacturing plants; • High prices and limited natural gas means industries such as ammonia will compete with other users of gas (e.g. electricity).
		Switching to other less carbon -intensive fuels and feedstocks (e.g. biomass and gas)	0.28		
		CCS	0.60	High	• Lack of data and research in the application of CCS to industrial processes such as cement or iron and steel
Transport	Road transport	Electric vehicles	0.17	High	• Battery cost reductions, charging infrastructure, and dependence on decarbonising electricity supply
		Biofuels	0.11	Uncertain	• Uncertainties in cost, availability of reliable, sustainable feedstock
		Vehicle efficiency	0.14	Low	• Rebound effect and growing preference for larger vehicles as incomes rise
	Non-road transport	Rail, water and aviation efficiency	0.20	Low to Medium	• Uncertainties in speed of penetration of newer aeroplane and ship hull designs
		Water, aviation biofuels	0.07	Uncertain	• Uncertainties in cost, availability of reliable, sustainable feedstock
		Rail electrification	0.19	High	• Large national rail infrastructure likely to be expensive to electrify
		Non-road: modal switch from domestic air to rail	0.11	Low	• Rail may not be competitive for very long-distance inter-city travel
Buildings		Low carbon heating	0.53	Negative to Low	• Increased use of CHP will require integrated urban planning • Heat pump savings rely on decarbonisation of electricity.
		Lighting, cooling and appliances	1.24	Negative to Low	• Savings rely on decarbonisation of electricity sector
		Energy efficiency in buildings	0.23	Negative to Low	• Undeveloped institutional structure to monitor and enforce building standards could struggle to keep up with growth in building stock

Total abatement by 2050: 7.6 GtCO$_2$ (compared to 10.4 GtCO$_2$ baseline emissions for these sectors)

Notes: Low Cost = \$0-50/tCO$_2$; Medium Cost = \$50-100/tCO$_2$; High Cost = over \$100/tCO$_2$

18. Industry accounts for more than half the carbon savings on the demand side, with the largest savings from increased electrification as the power generation sector decarbonises. Ensuring industrial plants operate at best available technology (BAT) levels and capturing industrial emissions from CCS will also be important drivers of emissions reductions.

19. In road transport, about two fifths of the savings come from electric vehicles, with the remainder from biofuels and vehicle efficiency. By 2050 all new vehicle sales are assumed to be either fully electric or hybrid. The critical factors for the adoption of electric and hybrid vehicles in China will be the need for R&D to increase battery energy density and reduce cost, the development of charging infrastructure, and consumer preference. The deployment of biofuels depends on availability of reliable and sustainable feedstock supplies and the setting and monitoring of standards. Urban design and systems can have a significant impact on vehicle ownership and usage – this has been considered to some degree through the assumption that Chinese levels of vehicle ownership will be lower than in OECD countries at equivalent income levels, though more detailed research would be required to specify urban network design. Most of the remaining savings in the transport sector will come from efficiency improvements in rail, water and air transport, and the electrification of railways.

20. In Imperial's analysis the business as usual scenario is assumed to lower emissions levels as buildings are replaced by 2050 with more efficient designs, and as lighting and appliance efficiency continues to increase. In the abatement scenario these emissions are reduced by more than 80%, a saving of 2.0 $GtCO_2$/year by 2050. This will depend on the widespread deployment of low carbon heating technologies such as heat pumps, the availability of low carbon electricity, and the development of a coordinated institutional system to monitor and enforce building standards.

RESOURCE IMPLICATIONS OF CHINA'S LOW-CARBON DEVELOPMENT PATHWAY

21. The abatement scenarios presented here imply a number of challenges to China's energy and resource usage. The considerable biomass production to provide the increased use of bio-energy in the industry and transport sectors will require a large area which could be provided by China's extensive grasslands, provided second generation biofuel technologies are further developed. Water consumption will also be a major consideration for biomass production, as well as for the location of low-carbon, more water-intensive electricity generation such as hydro and nuclear.

22. The IIASA Mix scenario implies oil demand which will continue to considerably exceed domestic oil production, though by 2050 oil demand in the Mix scenario will be less than half that in the Baseline, underlying the attractiveness of low-carbon transport to address this issue. Gas demand, however, would increase in the IIASA Mix scenario compared to the Baseline, which presents a number of challenges to China in terms of securing gas imports through pipelines and liquefied natural gas (LNG), as well as extracting its potentially considerable unconventional gas reserves. Coal demand would drastically reduce in the IIASA Mix scenario compared to the Baseline, which could be highly advantageous to China given the challenges it will face in mining its considerable coal reserves and transporting them to demand centres at an economic cost. And uranium supply will be a key strategic issue for China, as its reserves are relatively limited, although alternatives to current technologies exist (e.g. fast-breeder and thorium-based reactors) which could significantly reduce its demand.

CONCLUSIONS

23. The largest factor in the decarbonisation of China's energy sector to 2050 is the availability of low-carbon electric power. There is considerable uncertainty as to the relative costs of nuclear power, fossil power with CCS, hydro, PV, and wind. It makes sense to develop all these sources. However all low carbon options share the need for a strong, smart electric grid to access geographically diverse resources and to balance intermittent supply. China has already embarked on a major programme of grid investment, but given that a number of world regions will face shared challenges in decarbonising their electricity sectors, collaboration in grid design and the development of smart and storage technologies will be beneficial.

24. Energy efficiency across the industry, transport and buildings sectors will also be critical to achieving a low carbon pathway to 2050, perhaps more so than decarbonising electricity, depending on the view that is taken of business-as-usual energy efficiency improvements. Most of these measures are cost-effective and Imperial have been more optimistic than IIASA in assuming that such improvements will be achieved even in the Baseline scenario (which is why abatement figures in Table ES1 are relatively modest). These improvements depend on China's progress in building up its monitoring and regulatory institutions and in developing effective policies and support mechanisms to deliver higher cost low-carbon technologies. International collaboration, especially at city and provincial levels, where careful urban planning will be critical to limit uncontrolled growth of transport and heating emissions as population centres grow, could be valuable in areas where developed countries have greater experience to draw on.

25. Otherwise, the next most important factor is the adoption of CCS, especially if China develops a large energy conversion sector, including CtL. This underlines the need for early commercial scale development of CCS in electricity generation and, in addition, research into its applications to industry and fuel conversion. China is already involved in a number of international collaborations on CCS, including with the UK and Europe, but this should be an area of urgent international focus.

26. Low carbon electricity and CCS involve a number of medium and high cost options. It seems, therefore, that specific technology support, including a long-term, stable carbon price, will be required in order to ensure these technologies are successfully deployed to the scale required. China has signalled in its recent 12th Five Year Pan its goal of "gradually establishing a carbon trade market". There are numerous opportunities for international collaboration in this area, since such trading systems would require the development of robust measurement and reporting systems and careful system design – areas in which the UK and EU have considerable experience.

1 Introduction

1.1 China's 2009 CO_2 emissions were about 7.7Gt, having more than doubled since 2000 [3]. Two years (2003 and 2004) saw annual increases in emissions of greater than 15%, driven by a rapid expansion of heavy industrial sectors [4]. On business as usual assumptions, these emissions are projected to continue to rise rapidly with China's continued economic development, in some scenarios representing nearly 30% of global emissions by 2050[1]. This means that the future course of China's CO_2 emissions is of critical importance for climate change mitigation.

1.2 China has recognised the need for deep cuts in global emissions "with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius" [5]. However China's energy policy has multiple objectives. As explained in China's official statement to Cancun, "As a developing country with per capita GDP of only US$3,700 and ranking around 100th place globally, China still has a huge population living in poverty and is confronted with multiple challenges of economic development, poverty eradication, improving people's livelihoods and protection of climate" [6].

1.3 The security of energy supply, especially oil imports, is one of the most important energy policy objectives in China. China consumed an estimated 8.1 million barrels per day (b/d) of oil in 2009, with net oil imports of about 4.3 million b/d, making it the second-largest net oil importer in the world behind the United States, and these imports are set to increase [7]. Coal, which is the most carbon intensive fossil fuel, is also the lowest cost and most accessible source of energy in China. In 2009, coal made up 71% of China's primary energy usage [8], and four-fifths of electricity generation, in 2008 [9]. Coal-fired power generation is set to continue its rapid growth, with some 450GW of power plants at the planning, commissioning or installation stage [10].

1.4 Fossil fuel-related air pollution has also been a major energy-related issue for China for several years. Sulphur dioxide emissions in China reached a peak of just under 26Mt in 2006, before falling back to just over 22Mt (approximately their 2004 levels) in 2009 [11], partly as a result of the requirement for newer coal plants to fit flue-gas desulphurisation (FGD) equipment. However, a number of other pollutants such as particulate matter, nitrogen oxide and mercury remain a problem [12]. Moreover the strong growth in (oil-based) road transport in recent years has been a major source of urban air pollution from NO_X, hydrocarbons, CO and particulate matter (e.g. [13]).

1.5 China is clearly aware of the need to improve its energy efficiency and reduce its reliance on fossil fuels, which brings not only potential economic benefits such as security of energy supplies and a reduced oil import bill, but local and global environmental benefits as well. Its 11th Five Year Plan (2006-2010) set an ambitious target to reduce energy intensity (energy consumption per unit of GDP) by 20% on 2005 levels - in the event it achieved a 19.1% reduction [14].

1.6 In announcing the new 12th Five Year Plan (2011-2015) the Chinese Government has signalled even more clearly a focus on sustainability and the environment. Prime Minister Wen Jiabao said, "We must not any longer sacrifice the environment for the sake of rapid growth and reckless rollouts, as that would result in unsustainable growth featuring industrial overcapacity and intensive resource consumption" [15]. The Plan contains an overall economic growth projection of 7% p.a., significantly lower than actual growth in recent years. It also contains a number of energy and emissions targets including an energy intensity reduction of 16% and carbon intensity reduction of 17%, on 2010 levels. At the same time, the Plan sets out seven strategic emerging industries (SEIs) critical to China's economic development, including electric vehicles, energy efficient products and renewable energy. Investment in these industries will total approximately RMB10trillion ($1.5trillion) over the course of the Plan (to put this figure in context, in 2010 China's GDP was about RMB38trillion) [12]. The Plan also includes major increases in non-fossil energy, including a four-fold growth in nuclear power to 40GW, 63GW of new hydroelectric capacity, 48GW of new wind capacity and 5GW of solar capacity by 2015 [14].

1.7 China's Copenhagen Accord pledge includes a target to achieve a 40-45% reduction in carbon intensity by 2020, compared to 2005 levels, and to meet 15% of its primary energy demand from non-fossil sources by 2020. The 12th Five Year Plan proposes a target of 11.4% of non-fossil energy demand by 2015, against 8.3% in 2010. This rate of improvement would keep China broadly on track to meet its Copenhagen Accord pledge for non-fossil energy demand. As for the 12th Five Year Plan's proposed 17% reduction in carbon intensity by 2015, depending on the level of CO_2 emissions in 2010 and the actual level of economic growth during the 12th Five Year Plan period, China's emissions intensity may have to fall a further 20% or more on 2015 levels during the 13th Five Year Plan (2016 to 2020), in order to ensure that China achieves at least the bottom of its Copenhagen Accord pledge, i.e. to reduce its emissions intensity by 40% compared to 2005 levels.[3]

1.8 Looking beyond the 12th Five Year Plan and China's Copenhagen Accord target, there is considerable and increasing interest in China's potential long term pathways towards a low carbon economy, as part of a global effort to tackle climate change. The focus of the following sections is how China might achieve a significant reduction in emissions by 2050, and the implications of the scale-up in key low-carbon technologies for both China and other regions.

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[3] This estimate is uncertain as it depends on outturn CO_2 emissions in China for 2010. According to the EIA (2010), as presented at http://www.guardian.co.uk/news/datablog/2011/jan/31/world-carbon-dioxide-emissions-country-data-co2#data, CO_2 emissions in China were 5.5Gt in 2005, 6.8Gt in 2008, and 7.7Gt in 2009. If emissions were 8.5Gt in 2010, and if the 12th Five Year Plan carbon intensity target were met, then carbon intensity would have to fall by 23% on 2015 levels during the 13th Five Year Plan for the 40% Copenhagen Accord Pledge to be met (based on Imperial's own calculations). Some commentators have estimated that, since China's energy intensity in 2010 was 19% lower than in 2005, its carbon intensity in 2010 was about 20% lower than 2005 levels, which would imply that the 13th Five Year Plan would have to achieve a 10% reduction in carbon intensity on 2015 levels, assuming the 12th Five Year Plan's 17% carbon intensity reduction were achieved. However, this would also imply that 2010 emissions were 7.3 $GtCO_2$, lower than 2009 emissions, which seems unrealistic.

2 China’s emissions reduction trajectory

2.1 The IIASA MESSAGE model used for this study calculates the least-cost mix of technologies that would deliver a given level of energy demand, within a specified emissions limit. The model assigns emissions reductions to the regions of the world in which they would occur at least cost. The implications of these scenarios for burden sharing of emissions targets would, of course, also depend on the extent to which emissions reductions in less developed countries were funded by other regions (as would be the case with carbon market mechanisms such as the CDM, for example).

2.2 The model in its current form lacks sufficient geographical detail to model China on its own, instead modelling a “Central and Planned Asia” (CPA) region, of which China makes up about 90% of both GDP and population across the period 2010-2050[4]. This study analyses three IIASA emissions scenarios for the CPA region[5]:

- a “Baseline” scenario with no emissions limit;
- an “Efficiency” abatement scenario which emphasises demand side energy efficiency improvements, resulting in a developing country energy intensity reduction of over 3% per year compared to average reductions of less than 2% per year since 1970. In addition, the Efficiency scenario assumes a very low emissions floor can be achieved after 2050, resulting in a less aggressive reduction in emissions by 2050;
- a “Mix” abatement scenario with lower demand side energy efficiency improvements, a diverse mix of low-carbon energy supply technologies, and a more aggressive emissions reduction by 2050 compared to the Efficiency scenario. The Mix scenario allows emissions to peak at a slightly higher level than the Efficiency scenario.

2.3 Both the Mix and Efficiency abatement scenarios are part of global emissions scenarios which are aimed at limiting global warming to 2 degrees Celsius above pre-industrial levels[6]. Figure 2.1 shows the three scenarios’ emissions trajectories compared.

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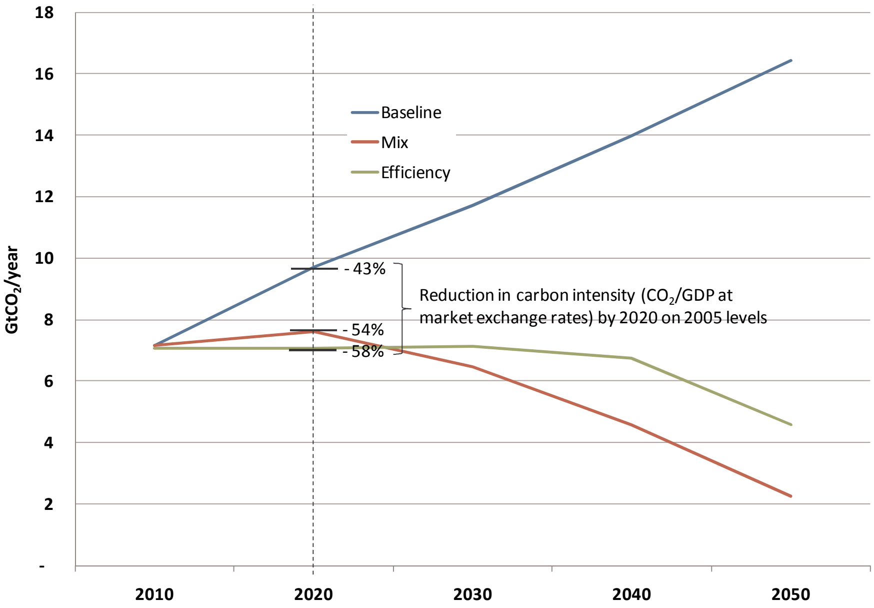
[4] The rest of the Central and Planned Asia region is made up of Cambodia, North Korea, Vietnam, Mongolia and Laos

[5] These scenarios are part of IIASA’s (forthcoming, June 2010) Global Energy Assessment study. See http://www.iiasa.ac.at/Research/ENE/GEA/index_gea.html and Annex A for details.

[6] According to calculations developed in Meinshausen et al [16], the probability of exceeding 2°C is less than 25% in both of the IIASA abatement scenarios (23% in Efficiency, 17% in Mix, compared to 85% in the Baseline). These estimates are dependent on assumptions about climate sensitivity.

Figure 2.1: CO_2 emissions trajectory for Central and Planned Asia region to 2050



2.4 Figure 2.1 shows that the Baseline emissions continue to grow to about 16 $GtCO_2$ by 2050. In contrast emissions growth peaks in 2020 in the Mix scenario and remains at a fairly flat level between 2010 and 2030 in the Efficiency scenario, before falling at an increasing rate to below 3 $GtCO_2$ (Mix) and below 5 $GtCO_2$ (Efficiency).

2.5 A number of other studies have presented analysis of China's possible emissions reductions to 2050, in many cases as part of global GHG trajectories that provide a reasonable chance of a 2^O Celsius limit to global warming. These also suggest that China's emissions would need to fall to around 5 $GtCO_2$ or less by 2050, with a peak sometime between 2020 and 2030 (see Annex B for a comparison of key assumptions in these studies).

2.6 Assuming China's Copenhagen Accord pledge of a 40-45% carbon intensity reduction on 2005 levels by 2020 were applied to the CPA region as a whole, the Baseline scenario would achieve the mid-point of the range presented in the pledge, which reflects that even the Baseline assumes significant improvements in energy and carbon intensity. Both abatement scenarios would actually achieve more than a 50% reduction in carbon intensity by 2020, relative to 2005 levels[7]. In other words, China's stated ambitions for carbon reductions to 2020 appear more consistent with the Baseline than with the abatement scenarios. This does not alter the message of the Mix and Efficiency scenarios that dramatic reductions in CO_2 emissions are achievable over the longer term. But it underlines the need for early action if these reductions are to be achieved. Imperial's own modelling, described in detail later in this report, suggests that provided key low-carbon technologies penetrate through the

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[7] This can be compared to the analysis in the Grantham Institute's previous study for the AVOID Programme, "Achievability of International Near Term Targets for CO_2 Emissions Mitigation ", which showed that a 54% reduction in carbon intensity by 2020 was only feasible in a very challenging "Stretch" scenario.

different sectors of the Chinese economy, the rates of emissions reductions to 2050 suggested by the Mix scenario are feasible.

2.7 These intensity targets are calculated on the basis of annual GDP growth of 7.1% in the decade 2010-2020 – broadly in line with China's 12th Five Year Plan target of 7% per year, although the 11th Five Year Plan target (7.5% per year) was significantly exceeded, with annual growth closer to 10% per year. Higher economic growth to 2020, without correspondingly higher growth in CO_2 emissions (as may be the case with a shift to lower carbon energy sources and away from the most carbon-intensive industry), would lower the region's carbon intensity by 2020.

2.8 Figures 2.2 and 2.3 show the make-up of emissions savings in both IIASA abatement scenarios relative to the Baseline scenario. For both scenarios, electricity generation, industry and energy conversion make up the majority of the annual savings by 2050. In the Mix scenario, transport is the single largest emitting sector by 2050, with annual emissions of about $0.8GtCO_2$. In the Efficiency scenario, electricity generation remains the largest emitting sector, with just over $2GtCO_2$ emissions.

Figure 2.2: CO_2 emissions in IIASA Baseline and Mix scenarios for the CPA region

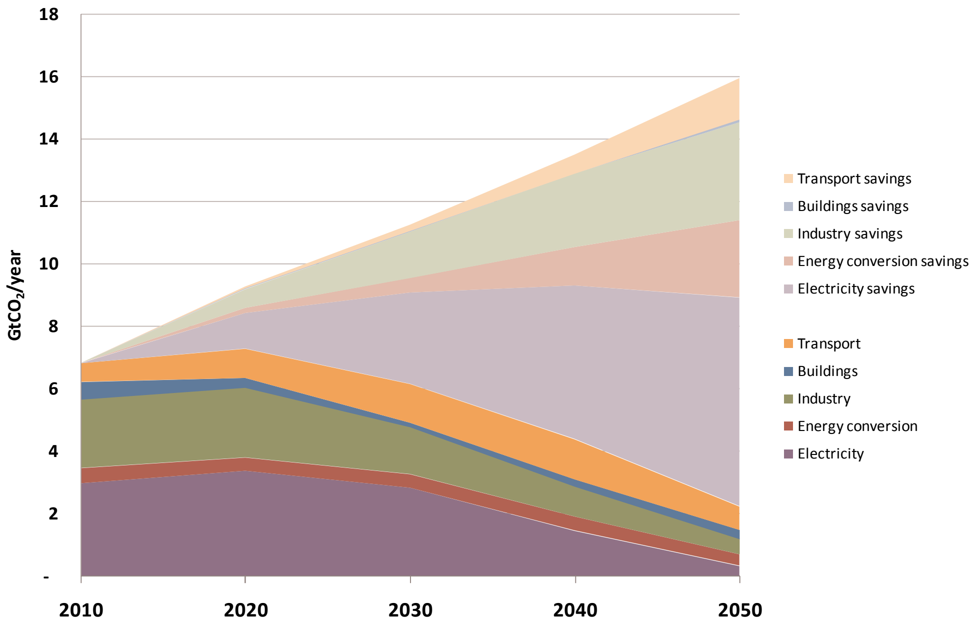
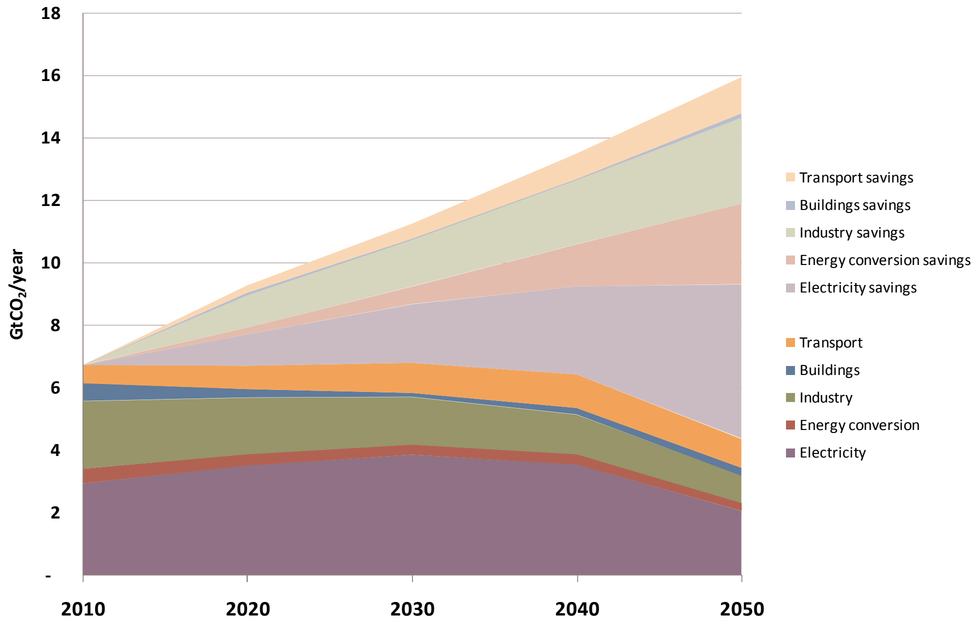


Figure 2.3: CO_2 emissions in IIASA Baseline and Efficiency scenarios for the CPA region

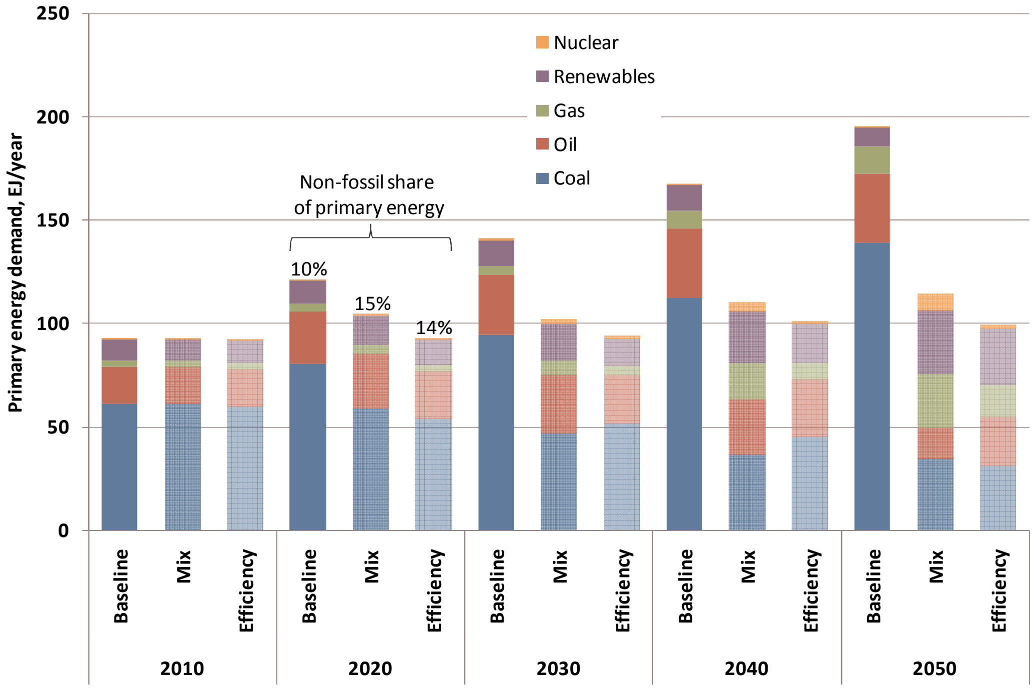


2.9 In the IIASA scenarios, the energy conversion sector is represented as a distinct sector in the energy supply system. This sector consists of the major processes required to extract and produce primary energy sources (principally coal, gas, crude oil and renewable biomass), and convert and distribute them for use as final energy (biogas and biofuels, hydrogen, coal-to-liquids and gas-to-liquids fuels, and oil products) in the energy end-use (transport, industry and buildings) sectors. In the Baseline scenario this sector is responsible for 2.8 $GtCO_2$ of annual emissions by 2050, 17% of total energy and industry CO_2 emissions by 2050. In both the Mix and Efficiency abatement scenarios, the sector emits approximately only 0.3-0.4 $GtCO_2$ by 2050. This dramatic reduction in emissions is largely the result of increased use of CCS technologies. In both the Mix and Efficiency abatement scenarios, all of the production of hydrogen (from coal and gas), biofuels (from biomass), and synthetic fuels (from coal and gas) happens with CCS. Whether this approximately 2.5 GtCO2 of abatement can be achieved in practice is therefore highly dependent on the future development of such CCS technologies.

2.10 Both the Mix and Efficiency scenarios result in significant reductions in overall fossil fuel dependence. Figure 2.4 shows the primary energy demand by fuel type in each of the Baseline, Mix and Efficiency scenarios. By 2020, non-fossil sources would make up 10% of total primary energy in the Baseline scenario, compared to 15% in the Mix and 14% in the Efficiency scenarios. This can be compared to China's Copenhagen Accord pledge to source 15% of primary energy from non-fossil sources by 2020 [17]. There is a significant reduction in coal demand from 2020 in both abatement scenarios, whereas in the Baseline scenario coal demand continues to increase throughout the period to 2050. By 2050 coal demand in the abatement scenarios is about a quarter of the Baseline scenario. In the Mix scenario oil demand continues to grow to 2030, and then declines to 2050, compared to a continued increase in the Baseline scenario. The Efficiency scenario sees oil demand grow more slowly to a similar level to the Mix scenario in 2040, before declining to 2050 more slowly than the level in the Mix scenario.

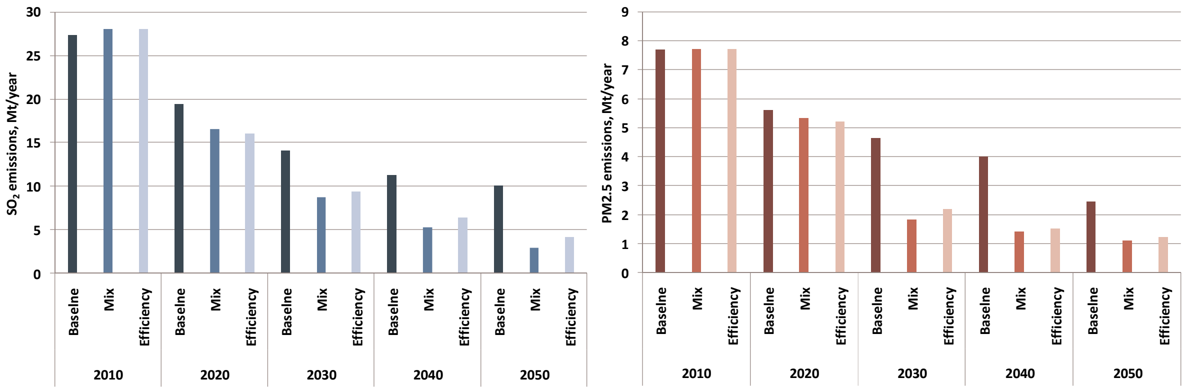
2.11 The most important factor in reducing coal and oil demand is energy efficiency and conservation, which in the Mix scenario reduces energy demand to just over half the level in the Baseline scenario by 2050. The other principal drivers of reduced coal and oil dependence in both abatement scenarios are (respectively) a marked increase in non-fossil power generation (as discussed in Section 3: Power sector) and the increasing electrification of, and use of bio-energy in, the transport sector (as discussed in Section 5: Transport sector).

Figure 2.4: CPA primary energy demand in the IIASA Baseline and abatement scenarios



2.12 As well as reduced dependence on fossil fuels, the abatement scenarios show a reduction in all major local air pollutants. Levels of two of the most damaging to health, sulphur dioxide (SO_2) and particulate matter (PM2.5) are shown in Figure 2.5. Levels of these pollutants fall even in the Baseline scenario, despite increased use of fossil fuels over time, as the scenario assumes that World Health Organisation recommended limits to local pollution are enforced. However, effective abatement of indoor and outdoor air pollution are specific objectives of the IIASA abatement scenarios, which lead to further reductions in these levels of pollutants – to less than half the levels in the Baseline scenario by 2050.

Figure 2.5: CPA SO_2 and PM2.5 levels in the IIASA Baseline and abatement scenarios



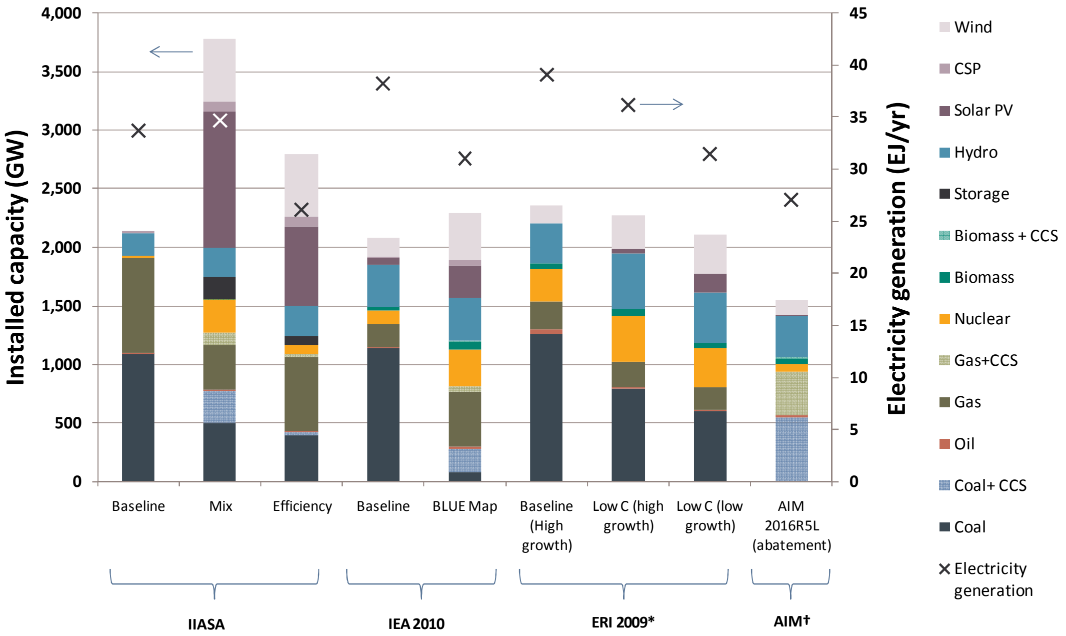
2.13 Consumption losses in the CPA region in the Mix scenario are about 2% of GDP in 2050. This would need to be compared against a projected growth in consumption of about 500% in the CPA region over the period to 2050. Expenditures on the energy and industry CO_2 emitting sectors are higher in the Mix scenario (3.1% of GDP by 2050) compared to the Efficiency scenario (2.5% of GDP by 2050), because the Mix scenario requires more extensive investment into decarbonisation technology.

2.14 The following sections of this study analyse in detail where the major emissions savings come from in the abatement scenarios relative to the Baseline scenario, and the challenges to scaling up low-carbon technologies to the degree required to make these emissions savings. They also consider the challenges that the Baseline scenario itself would pose, mainly in terms of fossil fuel supplies, energy security and pollution.

3 Power sector

3.1 In both abatement scenarios, the power sector will be the biggest underlying driver of emissions reductions on the supply side, as shown in Figures 2.2 and 2.3. The Mix scenario has a similar electricity demand to the Baseline scenario by 2050 as shown in Figure 3.1, as a result of increased electrification in the economy broadly offsetting energy demand reductions. However, the installed capacity is much higher than in the Baseline, as renewable sources with lower average load factors, such as solar PV and wind, are built in place of coal-fired generation plant, which has a much higher average load factor. The Efficiency scenario has about 20% less electricity demand than the Baseline and Mix scenarios, as a result of greater energy efficiency measures, which more than offset the increased electrification.

Figure 3.1: 2050 CPA electricity generation and capacity mix in IIASA Baseline and abatement scenarios, with other model outputs included for comparison



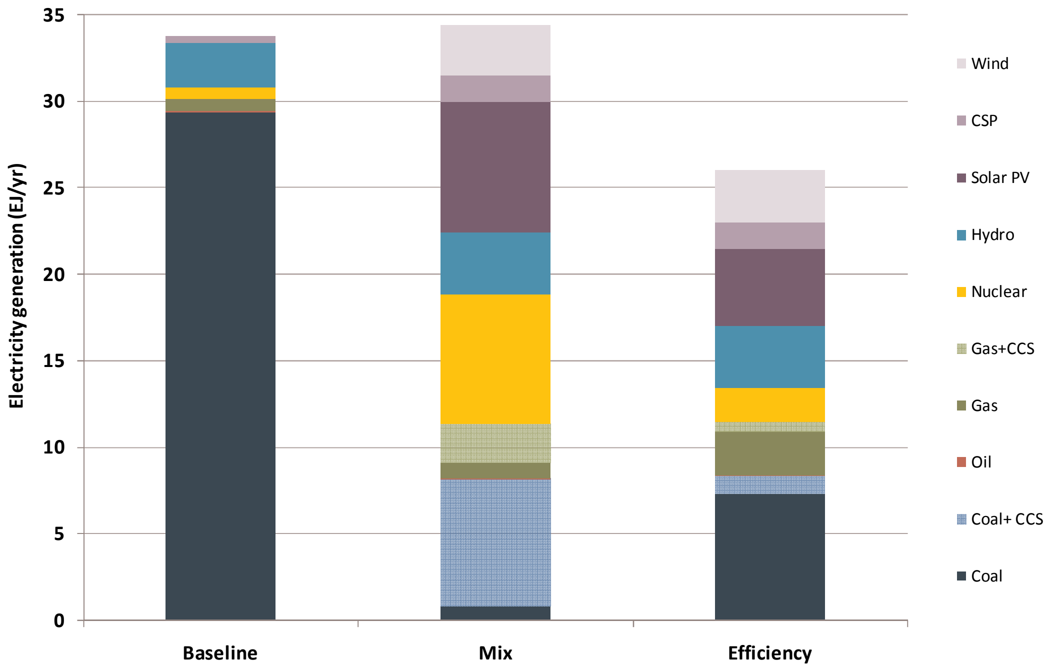
Notes: *ERI does not specify CCS or differentiate between solar PV and solar CSP
†AIM GW values calculated from energy values using IIASA Mix annual capacity factors

3.2 Whilst the IIASA MESSAGE model accounts for the lower load factors in intermittent renewable generation technologies, it is unclear the extent to which a radical increase in the use of smart grid technology, to better match the electricity supplied from variable renewable sources to demand, could decrease the required level of installed capacity. Specific spatial modelling of demand and supply in electricity networks would be beneficial in understanding the potential for this further.

3.3 It could be challenging for China to reduce the amount of non-CCS coal-fired generation capacity to the levels resulting from the abatement scenarios, given that so much new non-CCS coal plant (as discussed in Section 1, reportedly 450GW, with 260GW in the 12th Five Year Plan period alone) is due to start generating in the next few years. Much of this plant would have to be retrofitted with CCS equipment, or retired before 2050, indicating plant lifetimes of less than 40 years[8].

3.4 Figure 3.2 shows the electricity generated by technology type for each of the three IIASA scenarios, in 2050. This demonstrates that, in spite of the large capacity of gas plant in the Baseline scenario, the majority of generation is coal-fired. By contrast, in the Mix scenario there is little remaining coal generation (in spite of a large installed capacity, much of which is due for imminent retirement), with the majority of generated electricity from coal with CCS, nuclear, hydro, solar PV and wind - all zero or very low-carbon technologies. This results in a CO_2 intensity of electricity generation of less than 50g/kWh[9], compared to 750g/kWh in the Baseline scenario. In the Efficiency scenario, which has lower electricity demand than the Mix scenario, and which also has a higher level of overall emissions in 2050, electricity CO_2 intensity is about 280g/kWh, with non-CCS coal still the largest contributor to generation.

Figure 3.2: CPA electricity generation by technology in the IIASA Baseline and abatement scenarios



3.5 It should be noted that switching from coal to gas-fired generation, which occurs in all three IIASA scenarios, is somewhat speculative given that there are significant uncertainties over the future

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[8] It should be noted that analysts from Tsinghua University (in comments to Imperial College on a first draft of this paper) have deemed it reasonable to expect coal plant lifetimes of 20 to 30 years, and that much of the new coal plant can be retrofitted with CCS, indicating that the substantial planned new capacity of coal plant could be consistent with even those scenarios showing relatively little non-CCS coal by 2050.

[9] This figure is extremely low but to put it in context, the Committee on Climate Change has recently advised the UK government to decarbonise its electricity system to around 50g/kWh or lower by the 2030s [18].

availability of gas resources in China (both conventional and unconventional, as discussed in Section 8: Cross cutting issues), and the extent to which these would be prioritised for use in different sectors of the economy (e.g. in home heating, industrial usage, or electricity generation).

3.6 The power generation mixes in the IIASA scenarios are determined by a consideration of the relative costs of the different generation technologies and how these could develop in the future. Figure 3.3 compares the IIASA levelised costs with ranges of estimates derived from the literature. This shows that IIASA are relatively optimistic about the cost reductions possible for solar PV, wind and nuclear, but actually less optimistic about costs of coal and coal with CCS. Imperial College's own analysis suggests that there could be barriers to the continued cost reductions of solar PV, and that the lower end of the IIASA cost range by 2050 is possibly too optimistic (further details of the cost prospects for solar PV are given in Annex D)[10]. This leads to a build-out of solar PV in both IIASA abatement scenarios which is much higher than those in comparable studies, whilst by contrast, nuclear and hydro are relatively under-deployed compared to other studies.

3.7 Hydro, in particular, is likely to be deployed to a greater extent than indicated in the IIASA scenarios, which in both the Mix and Efficiency cases show only 250 GW of capacity by 2050. China already has 200 GW of hydro, and has a 2020 target to deploy 380 GW of hydro [19]. As concerns nuclear, there remain considerable uncertainties in the wake of the recent Fukushima incident around the future speed and level of deployment of the technology in China, but recent statements have indicated that plans to 2020 and beyond may not be very greatly affected [20]. This aside, a number of recent studies have projected a considerable deployment of nuclear by 2050. The IEA's Energy Technology Perspectives 2010 BLUE Map scenario has 318 GW of nuclear by 2050, whilst China's Energy Research Institute (ERI) has a range of 337 - 388 GW by 2050 in its low carbon scenarios. These scenarios are illustrated in Figure 3.1 for comparison purposes.

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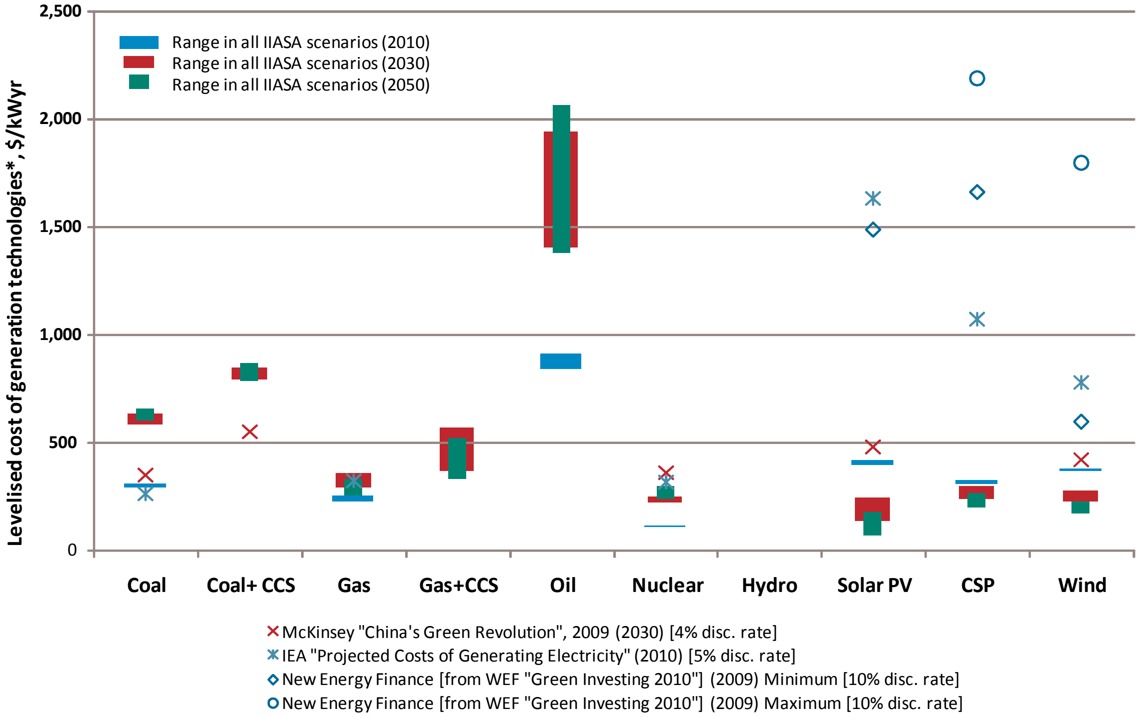
[10] This view is borne out by comments from reviewers at Tsinghua University, who believe that the IIASA solar PV cost estimates are very optimistic at the low end of the cost range.

Figure 3.3: Levelised cost comparison for low-carbon generation technologies



Notes: *Year of applicability stated in brackets; Values are China-specific excepting the Greenpeace/EPIA report; IIASA values are calculated using a 5% discount rate; New Energy Finance gives a 'maximum' value for Solar PV of $3945/kWyr, not shown here for clarity; Biomass is not included due to the uncertainty in fuel prices; CCS does not include transportation and storage, but includes an efficiency de-rating and the additional investment and operating costs. Uranium fuel cycle costs are not included here, but can be expected to account for 10-30% of the total electricity cost [21], [22]. Data sourced from McKinsey 2009 [23], IEA 2010 [21] , NEF 2010 [24].

3.8 There will be a number of challenges involved in scaling up each of the major low-carbon power generation technologies in the abatement scenarios, as shown in Table 3.1 (with further detail in Annex D), based on discussions with technology experts at Imperial College and further literature searches. Continued investment in R&D to bring down the costs of solar PV and to commercialise CCS will be critical factors to achieving the large penetrations of these technologies. Continued support for wind power will also be essential to ensure its deployment. Nuclear could also be a key technology, requiring careful consideration of access to uranium supplies, through either more efficient fast-breeder reactors or alternative (thorium) fuel reactors. And the changing climate and its effect on rainfall and water availability will be key considerations for a number of power technologies, especially hydro power.

3.9 In addition, one of the greatest challenges in providing decarbonised electricity will be in balancing the system to ensure that supply meets demand, as responsive generation plant such as coal-fired plant (whose output can be varied relatively quickly in response to demand variation) is replaced by variable output renewables (wind, solar), or nuclear which is currently best suited to base load generation. China's wind, solar, and hydro resources are highly dispersed geographically, and the development of a strong long distance grid will be essential to exploit them fully, as discussed further in Section 8: Cross cutting issues.

3.10 There are a number of potential areas for collaboration with the international community to help ensure the successful scale-up of the range of low-carbon generation technologies considered here. China would most likely benefit from international collaboration to adopt a domestic production capability in upstream production stages of solar PV wafer manufacturing, which would help its manufacturers to vertically integrate across all production stages and thereby help to bring down costs. For nuclear technologies, China could benefit from collaboration to develop a domestic capability in pressure vessel construction, uranium enrichment and reprocessing. For offshore wind, the UK in particular has experience of the installation and maintenance of turbines, which will be increasingly deployed in China. And the international community should build on its collaborations with China in CCS, to ensure this can be deployed at commercial scale as quickly as possible.

3.11 A number of regions face a shared challenge in integrating increasing penetrations of renewable technologies into their electricity generation, transmission and distribution systems. There will be a number of opportunities to collaborate on technologies which balance supply and demand such as smart grids and storage technologies, as well as modelling techniques to forecast wind availability.

3.12 The investment required to scale-up many of the low-carbon generation technologies in the short and medium term, and the use of CCS in the long-term, points to the need for a stable, long-term mechanism for the pricing of carbon. Further, this is a key area in which the international community, particularly the EU and the UK, has experience to share with China. Until now, the 12th Five Year Plan has stated the goal of "gradually establishing a carbon trade market", but does not elucidate with further details or a timeframe. Pilot schemes have been mooted, with the likely targets suggested as Guangdong, the low carbon cities and provinces, or perhaps single sectors, with Government-owned enterprises likely to lead trials. The areas for collaboration are varied, since such schemes would require the development of robust measurement and monitoring capability, as well as careful regulatory planning ([25], [26]). The UK and EU have considerable expertise in these areas.

Table 3.1 Challenges to scaling up the key low carbon power generation technologies in China

Technology	2050 capacity (GW)	Status of technology in China/ abroad	Key challenges to scale-up to 2050 levels
Solar	PV 1,200, CSP 90 (Mix); PV 700, CSP 90 (Efficiency)	• Silicon solar PV is a mature, proven technology. • China is currently the largest producer of solar PV cells. The largest user at present is Germany, with Spain, Italy, the US and Japan significant users. • Solar CSP is a mature and proven technology with over 1 GW installed globally.	• For silicon PV, cost reduction is still a key challenge, through integration of production processes such as Si purification and wafer manufacture; • The embedded energy and carbon of silicon PV is significant compared with other renewable technologies. Newer technologies e.g. thin-film PV are likely to improve this; • Water is a constraint for CSP. The success of closed-cycle or air-cooled CSP plants will be critical for the growth of CSP; • Distributed solar PV and variable output for both solar PV and CSP will require careful integration of a long-distance grid.
Nuclear	290 (Mix) 80 (Efficiency)	• Chinese domestic technology is currently Generation II and II+ (CPR 1000 PWR); • Currently importing foreign Generation III technologies, but likely to have the capacity to develop own Generation III by 2020; • Nuclear capacity at present in China is modest, at less than 10 GW up to 2010, but there is an ambitious target of 70 GW installed in total by 2020.	• Manufacturing of certain specialised parts (e.g. the pressure vessel, large pumps and valves) is only done by a small number of companies world-wide; • China will rely heavily on uranium imports in 2050. Use of thorium, enhanced fuel reprocessing and fast-breeder reactors would relax this constraint significantly; • Development of load-following capabilities – e.g. Light water reactors; • Following the events in Fukushima in March 2011, safety and public acceptance will be critical.
Wind	530 (Mix) 530 (Efficiency)	• China's wind market is relatively new, but already the largest in the world with over 42 GW installed by 2010; • Recent announcements from China specify offshore wind as an important area for growth in the near future [27].	• Grid connectivity is a key bottleneck at present, which needs to be addressed as scale-up increases; • Development of a domestic capability in large turbine technology is a key challenge - relatively small number of technical experts.
Hydro	250 (Mix) 250 (Efficiency)	• China has a number of large hydro plants as well as many smaller plants. These total nearly 200 GW as of 2010.	• Geographical separation of resource and demand; • Delays and increased costs due to environmental risk and population displacement are a major barrier for hydro – careful planning will be required.
IGCC	110 (Mix) 10 (Efficiency)	• Known technology but relatively few fully operational plants in the world; • Still an immature technology in China – plans are underway to construct a IGCC demo plant.	• Uncertainty in the cost of IGCC is a key barrier; • Requires additional steps such as gasification and air separation which carry an efficiency penalty particularly with lower quality coals.
CCS	Coal 290, Gas 90 (Mix) Coal 40, Gas 30 (Efficiency)	• Urgent need for 'large-scale integrated projects' (LSIPs); Currently nine LSIPs in operation worldwide; • PC and IGCC pilot plants under development in China, investigation into EOR potential; • Estimated onshore CO_2 storage capacity in China is 2300Gt – 91% of large plants are within 100 miles of storage.	• High cost and technical uncertainty; • Increase water and fuel consumption (due to efficiency penalty) will place increased strain on China's scarce water resources and speed up the depletion of China's coal reserves; • Technology 'lock-in' as new plants are built – cost of retrofitting plants for CCS is higher; • Uncertainty surrounding the likelihood of a binding carbon price.

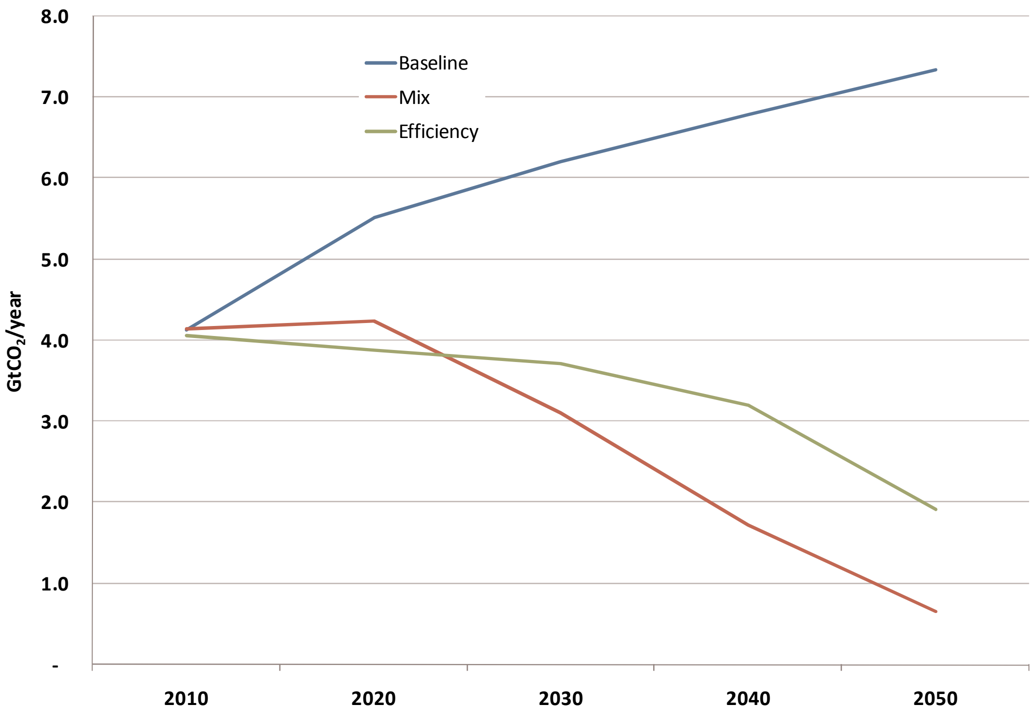
4 Industry

4.1 Total final energy consumption in industry accounted in 2007 for more than two-thirds of total Chinese energy consumption [11]. China significantly increased its energy intensive industrial output during 2003 and 2004, with a particular focus on iron & steel and cement manufacture, which together account for 77 % of all industry CO_2 emissions [1].

4.2 Looking forward, industry's share of economic output is expected to decline over the coming decades [2], as China's economic structure shifts towards less energy-intensive manufacturing and service sectors. Given the size of industrial emissions, the rate at which this shift occurs will be critical to determining the overall emissions – and emissions reduction potential – in China. Where China's energy-intensive manufacturing share declines because it shifts to other countries and regions, this would not necessarily result in a reduction in emissions.

4.3 IIASA's Baseline scenario projects emissions from industry (including indirect emissions from electricity usage) will be 7.3 $GtCO_2$ in the CPA region by 2050, about 45% of total CO_2 emissions in the region. By contrast, industry is projected to emit 0.7 (Mix) - 2.0 (Efficiency) $GtCO_2$ in 2050 in the IIASA abatement scenarios, 29% of total CO_2 emissions in the Mix scenario and 42% in the Efficiency scenario. Figure 4.1 below shows the emissions savings in each abatement scenario relative to the Baseline.

Figure 4.1: CPA Industry CO_2 emissions in the IIASA Baseline and abatement scenarios

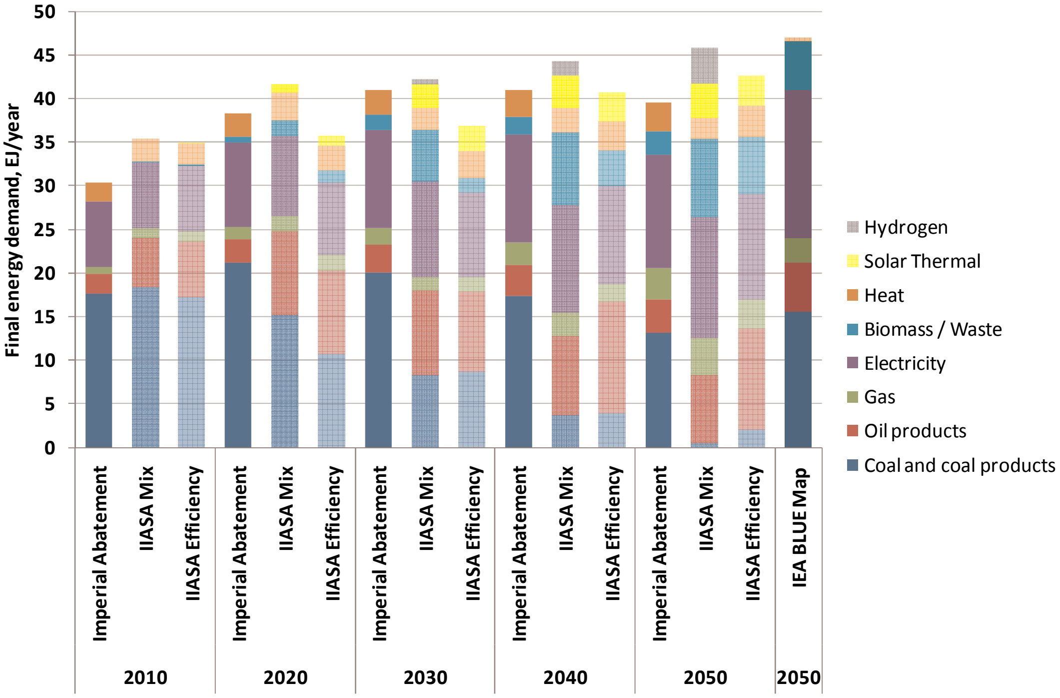


4.4 IIASA uses aggregated assumptions on the trends in energy demand (split by energy type) in the industry sector. In order to assess the specific abatement options which would achieve an emissions reduction broadly in line with IIASA's scenarios, Imperial has developed a bottom-up model of the industry sector in China, examining the potential for reductions in energy intensity, fuel switching to lower carbon fuels, and CCS in industry sectors. A detailed description of the modelling methodology is given in Annex C, however, the key assumptions are as follows:

- Industry was divided into 8 manufacturing sectors: Iron & steel, Chemical & petrochemical, Non-ferrous metals, Non-metallic minerals (largely cement), Machinery & transport, Food & tobacco, Pulp & paper and other (including Construction and Textiles);
- Total energy demand by sector was determined from projections of production rates and improvements in energy intensity. Adoption of Best Available Technology (BAT) and efficiency improvements in the iron & steel and cement sectors were modelled in detail including penetration of electric arc furnaces in the iron & steel sector and advanced New Suspension Preheater (NSP) kilns in cement. Carbon capture and storage was modelled for the iron & steel and cement sectors, accounting for the increase in energy intensity due to added energy requirements for capture;
- Total emissions were determined from fuel shares and the emissions factors of each fuel type. Estimates of how the fuel share for each sector would change were made using the 2005 fuel mixes of other industrialised countries (e.g. United States, Korea, Germany and Australia);
- Electricity CO_2 intensity is taken from the IIASA Mix scenario.

4.5 Figure 4.2 shows the energy demand comparison between the Imperial and IIASA abatement scenarios. Overall energy demand in the Imperial abatement scenario is within 14% of the IIASA Mix for all years[11]. The projected energy mix for the different scenarios varies considerably. The most notable difference is the share of coal and coal products. Both IIASA's mix and efficiency scenarios show a large reduction in the share of coal and coal products (energy demand from coal in 2050 is 0.6 EJ/yr and 2.1 EJ/yr in the Mix and Efficiency scenarios, respectively). It should be noted that this reduction is very large and represents an extreme example of what might be achievable. It is likely that the two sectors with high coal usage, the non-metallic minerals and the iron & steel industry, will peak between 2020 and 2030, resulting in a sharp decrease in construction of new plants as well as coal usage. However, there are limited options for substitution of coal in industrial applications, and a number of these technologies are still in the research phase and are very far from commercialisation. Therefore, the Imperial abatement scenario assumes a more conservative penetration of these technologies, giving an energy demand from coal in 2050 of around 13.1 EJ/yr in the abatement scenario, which compares well with that of the IEA BLUE Map scenario of 15.5 EJ/yr.

Figure 4.2: Industry energy demand comparison between Imperial and IIASA abatement scenarios



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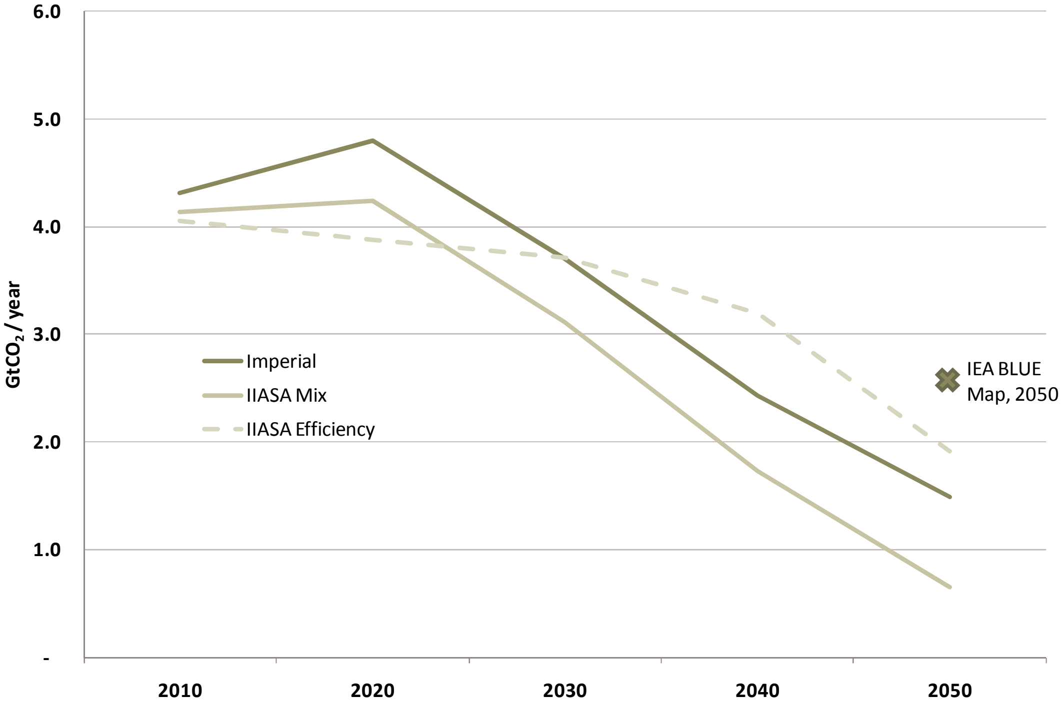
[11] Owing to inconsistencies in the definitions of industrial sectors, there is considerable variation in the range of estimates for current industrial energy demand in China: Estimates for industrial energy use in China in 2005 range from 20.3 to 30.9 EJ/yr [28], [29], [2].

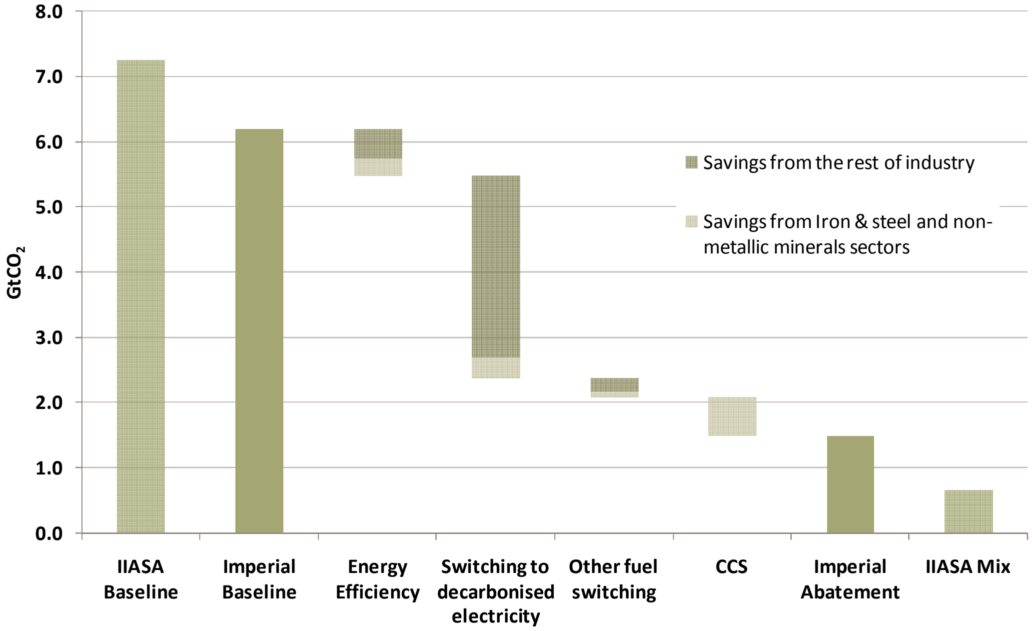
4.6 Figure 4.3 shows the resulting emissions (direct, process and indirect) in each of the abatement scenarios. Imperial's scenario shows higher emissions than both IIASA abatement scenarios to 2020 but thereafter declines to a level between the IIASA Mix and Efficiency scenarios, decreasing to 1.5 $GtCO_2$ in 2050. This is about 40% lower than the emissions projected by the IEA BLUE Map scenario of 2.6 $GtCO_2$ in 2050, due to the higher emissions factor of the electricity sector in the IEA BLUE map scenario of 121 g/kWh by 2050. The large emissions reduction observed in the IIASA Mix scenario is due to a combination of fuel switching away from coal and combined with almost complete decarbonisation of the power sector, reaching an emissions factor of below 50 gCO_2/kWh by 2050.

Figure 4.3: Industry emissions comparison between Imperial and IIASA abatement scenarios



4.7 Figure 4.4 shows a breakdown of the emissions savings in the industrial sector for China in 2050 in the Imperial abatement scenario, with the IIASA Baseline and Mix scenario for comparison purposes. Owing to the significant contribution of iron & steel and non-metallic minerals (largely cement) manufacturing to overall emissions, the figure also shows the share of savings from these sectors. Switching to decarbonised electricity results in the largest emissions savings. This is a result of using the electricity CO_2 intensity in IIASA's Mix scenario, where by 2050 electricity is highly decarbonised.

Figure 4.4: 2050 industry emissions savings in Imperial abatement scenario, by sector and measure



4.8 In many cases the emissions savings in the Imperial abatement scenario could be achieved at low or negative costs, as shown in Table 4.1. However, the largest element of emissions savings is linked to the decarbonisation of electricity. There will be several challenges to scaling up the requisite technologies and measures, also shown in Table 4.1. In addition, CCS for industry, which could make a sizeable contribution to overall industrial emissions savings, is still not a commercially demonstrated technology, and its potential cost means that it is likely to require targeted support in the early stages of its development, and some form of long term, stable carbon price to ensure it is economic for industry to commercially deploy it. The development of industry CCS is an urgent priority for the international community to realise this important abatement option. A detailed assessment of key technologies in the industry sector is included in Annex D.

Table 4.1: Summary of abatement options in the Chinese industry sector

Technology	2050 abatement potential (Gt CO_2)	Abatement cost range*	Status of technology in China/ abroad	Key challenges to scale-up to 2050 levels
Best available technology (BAT) and energy efficiency	0.71	Negative to low	• While some efficient, new plants with BAT exist in China, most of the Industrial sector is highly disaggregated with a large number of small, inefficient plants. The efficiency gap of these plants is large, and recent policies have sought to close down many of these (e.g. Top 1000 industries Programme [30]).	• Potential for further consolidation in energy-intensive sectors (to accelerate the spread of BAT) in new plants is becoming limited; • Local iron ore and bauxite is poor quality which limits efficiency improvements; • High quality coal for coking will compete with other uses (e.g. In power); • Some of the BATs need gas as fuel, which availability is limited in China.
Switching to decarbonised electricity	3.10	Medium	• The share of electricity in industry in China is low (24% in 2005 compared to an OECD average of 31% [28]. • In the steel industry, the share of Electric Arc Furnace (EAF) steel production in China is around 15% - limited by availability of scrap, which is currently imported [31].	• In the steel industry, scrap availability is a key limitation. It is uncertain whether China will be able to increase steel recycling to levels of developed countries (~30%) which would be required to meet scrap demand [32].
Switching to other less carbon - intensive fuels	0.28		• Over 20 yrs experience of biomass/waste co-firing in cement kilns worldwide. Leading countries are Netherlands (Substitution rate (SR): 83%) and Switzerland (SR = 48%); • Biomass co-firing in China is currently low. The potential for biomass/waste co-firing in China is good – owing to widespread availability and underutilisation of biomass residues/wastes; • 70% of world Ammonia production is from natural gas (cf 20% in China); • Biomass CHP in pulp and paper industry is widely used in developed countries	• Uptake of biomass substitution depends on a distribution network – relies on geographical proximity of fuel sources to manufacturing plants; • High prices and limited natural gas reserves will limit Ammonia production from gas. Moreover, gas usage might be prioritised for usage in the power sector (as backup capacity) or in buildings (to increase air quality).
CCS	0.60	High	• China's estimated viable storage capacity is about 2000 Gt. • The application of CCS to industry is still in the research/early demo phase: FINEX and HIsmelt demo plants • Carbonate looping is a promising technology for capture from cement plants (Cemex has a pilot plant in Monterrey, Mexico) • Oxy-fuel combustion has been demonstrated in the steel industry, and the related oxy-coal combustion method is currently being demonstrated [from IEA CCS Roadmap]	• Lack of data and research in the application of CCS to industrial processes such as cement or iron and steel. • High uncertainty in the costs and emissions reduction potential. Highly dependent on early demonstration of feasibility • Most cement plants will need to be retrofitted, since cement production is expected to peak by 2020 • Iron and Steel production is estimated to peak around 2030. Since CCS retrofit of steel plants is difficult, early rollout of CCS-ready plants is crucial

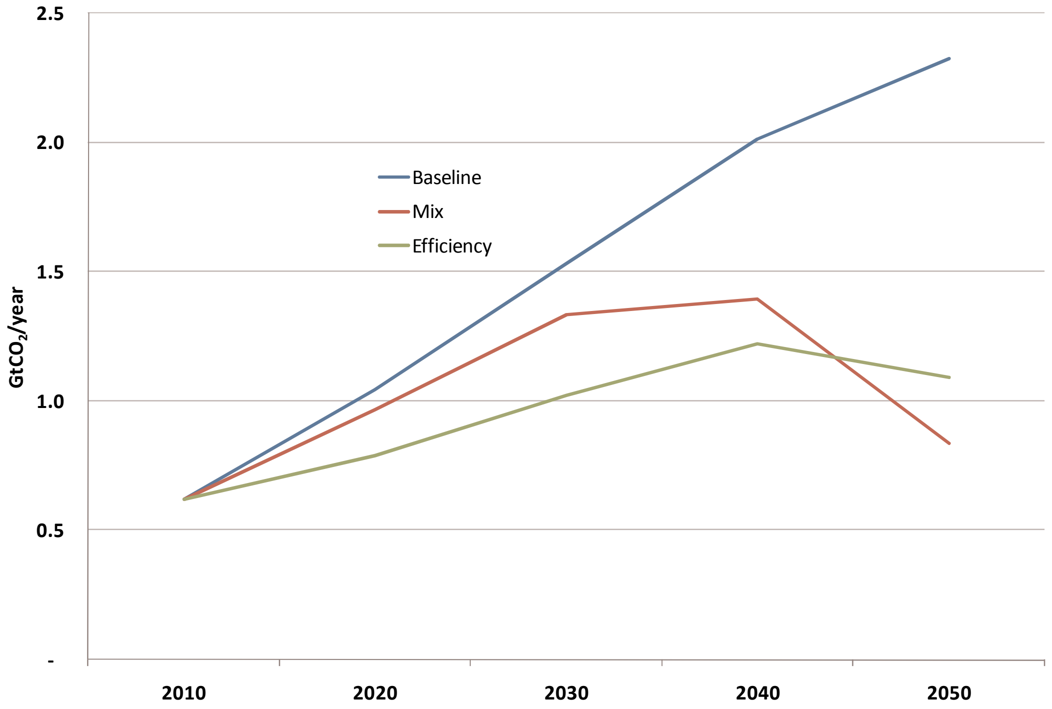
Notes: *Low Cost = $\$0\text{-}50/\text{tCO}_2$; Medium Cost = $\$50\text{-}100/\text{tCO}_2$; High Cost = over $\$100/\text{tCO}_{2,}$ using Imperial judgements based on a range of sources (see Annex E)

5 Transport

5.1 Transport accounted for 7% of total Chinese CO_2 emissions from fossil fuels in 2008 [4], with emissions from this sector having grown almost five-fold since 1990 [7]. This has been driven in large part by rapid growth of road vehicles – in 2007 there were about 45 million vehicles on the road, about three times the number in 2000 and about eight times the number in 1990. Passenger vehicles are a major component of this growth, with annual growth rates above 20% in recent years. In 2007 passenger vehicles made up three quarters of all road vehicles, compared to about a third in 1990[12]. With increasing incomes it is expected that this growth will continue – how quickly is uncertain and a major area of sensitivity in transport emissions projections.

5.2 IIASA's Baseline scenario projects emissions from transport to be 2.3 $GtCO_2$ in the CPA region by 2050, about 14% of total CO_2 emissions in the region. Due to rapid growth of this sector, it is projected that transport (including direct emissions and indirect emissions from electricity) will emit 0.8 (Mix) - 1.1 (Efficiency) $GtCO_2$ in 2050 in the IIASA abatement scenarios, 37% of total CO_2 emissions in the Mix scenario and 24% in the Efficiency scenario by 2050. Figure 5.1 shows the emissions in each IIASA abatement scenario relative to the Baseline.

Figure 5.1: Transport emissions in the IIASA Baseline and abatement scenarios



5.3 In order to assess the specific abatement options which would achieve an emissions reduction broadly in line with IIASA's scenarios (which specify energy demand and energy mix levels, but not the specific low-carbon technologies that would drive these), Imperial has developed a bottom-up model of the transport sector in China, examining the potential for low-carbon fuels (principally increasingly

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[12] Based on figures from China National Bureau of Statistics

decarbonised electricity and biofuels) and energy efficiency in the transport sectors. The modelling methodology is described in detail in Annex C. The key assumptions are as follows:

- **Road transport:** The vehicle population in China increases to 320 million by 2050, in line with assumptions made by IIASA; Electric vehicles increasingly penetrate the market, with sales of electric vehicles accounting for 40% of new vehicle sales by 2050; By 2050, hybrid vehicles (all variants including mild, full and plug-in) account for the remainder of sales; Biofuels consumption reaches 70 million tons of oil equivalent[13];

- **Non-road transport:** Rail is fully electrified by 2030, with a one third improvement in energy efficiency by 2050 compared to 2010; biofuels increase their share of air transport fuel to 20% and of marine transport fuel to 30%[14];

- **Electricity:** the carbon intensity is assumed to be that of the IIASA Mix abatement scenario.

5.4 Figure 5.2 shows the energy demand comparison between the Imperial and IIASA abatement scenarios. Overall energy demand in the Imperial model is higher than both the IIASA Mix and Efficiency levels in 2020 and 2030, then falling to a similar level to the IIASA Mix scenario thereafter. The composition of energy types is somewhat different between the scenarios, with the Imperial scenario showing a greater use of oil products, a slightly greater use of biofuels, but a more limited use of electricity, by 2050. The latter assumption is highly sensitive to projections on rail electrification and activity (passenger-km) levels.

5.5 Figure 5.3 shows the resulting emissions in each of the abatement scenarios. Imperial's abatement scenario shows higher emissions than both of IIASA's abatement scenarios to 2020, but peaks in 2030 and falls to a level between the IIASA Mix and IIASA Efficiency scenario by 2050. Emissions for both IIASA abatement scenarios peak in 2040. The IEA BLUE Map figures have been included for order of magnitude comparison purposes only, as they include full well-to-wheel emissions levels, as opposed to emissions directly from final energy usage in transport as in the Imperial and IIASA scenarios.

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[13] As projected by Ou et al [33], proportionally scaled with the oil consumption for the vehicle population assumed in this study

[14] Non-road transport assumptions are based on discussions with Stockholm Environment Institute, and are discussed in further detail in Annex C

Figure 5.2: Transport energy demand comparison between Imperial and IIASA abatement scenarios

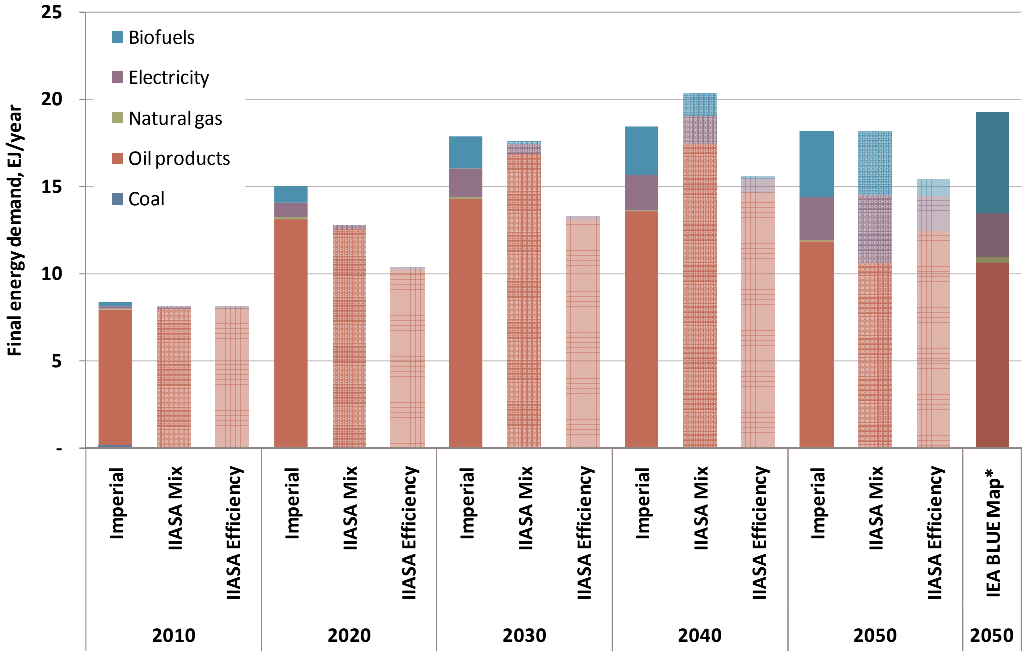
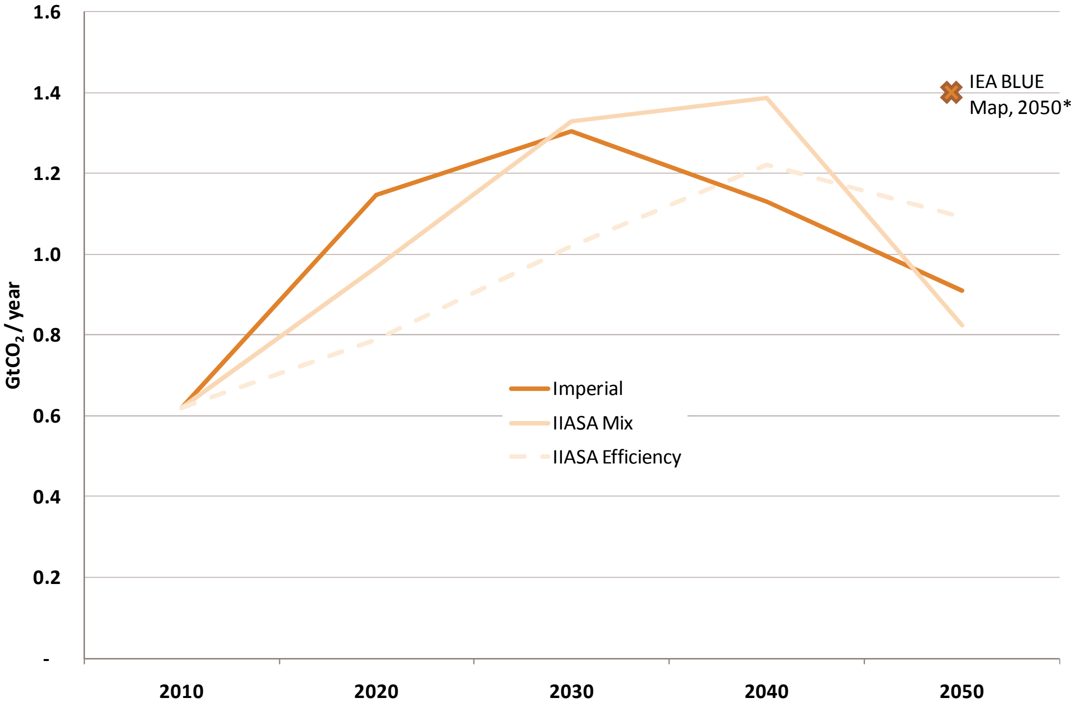


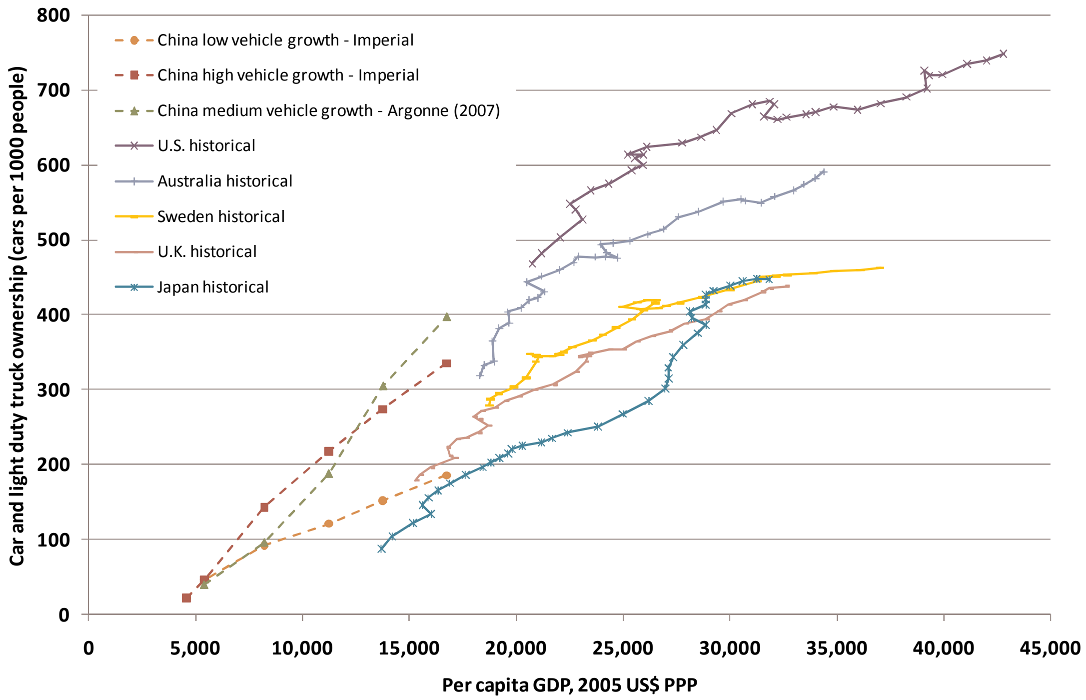
Figure 5.3: Transport emissions comparison between Imperial and IIASA abatement scenarios



Notes: *IEA BLUE Map scenario energy usage and emissions are on a well to wheels (rather than final energy) basis; IEA figures exclude hydrogen (approximately 1 EJ of energy demand in 2050)

5.6 A key driver of the Imperial scenario is its assumption on road transport vehicle growth. Although the scenario is based on Ou et al's [33] assumptions on penetration of electric vehicles, hybrids and biofuels, it takes a much lower 2050 vehicle population – of the order 300 million vehicles by 2050 (in line with IIASA's projections), as compared to 500 million vehicles projected by Ou et al [33]. Figure 5.4 shows the potential growth paths of vehicles in China compared to the historic levels in other countries, at different levels of per capita income. The Imperial high growth scenario shown is based on Ou et al's [33] growth rates, and the low growth on IIASA's. Section 7: Total emissions savings, discusses the emissions impact of taking the Imperial high vehicle growth scenario. A key challenge for China to achieve the levels of emissions indicated in this study will be its future urban and integrated transport and land use planning, and whether it can limit vehicle growth to, for example, Japanese levels, as is more in line with the Imperial Low scenario. Section 8: Cross cutting issues, highlights some of the potential and challenges around effective urban planning.

Figure 5.4: China's road vehicles projections and historical data for other countries[15]



5.7 There are a number of other potential low-technology pathways for transport, with the IEA (2010) ETP for example identifying significant hydrogen demand in 2050. Natural gas could also play a larger role than indicated, but this depends on the availability of resources in China (as discussed in Section 8: Cross cutting issues), and alternative demands for gas in other sectors such as electricity generation and transport.

5.8 Figure 5.5 shows the emissions savings in the Imperial abatement scenario against the Imperial Baseline scenario, by transport mode and major abatement measure, with the IIASA Baseline and Mix scenarios for comparison. Road transport makes the largest overall contribution to emissions savings

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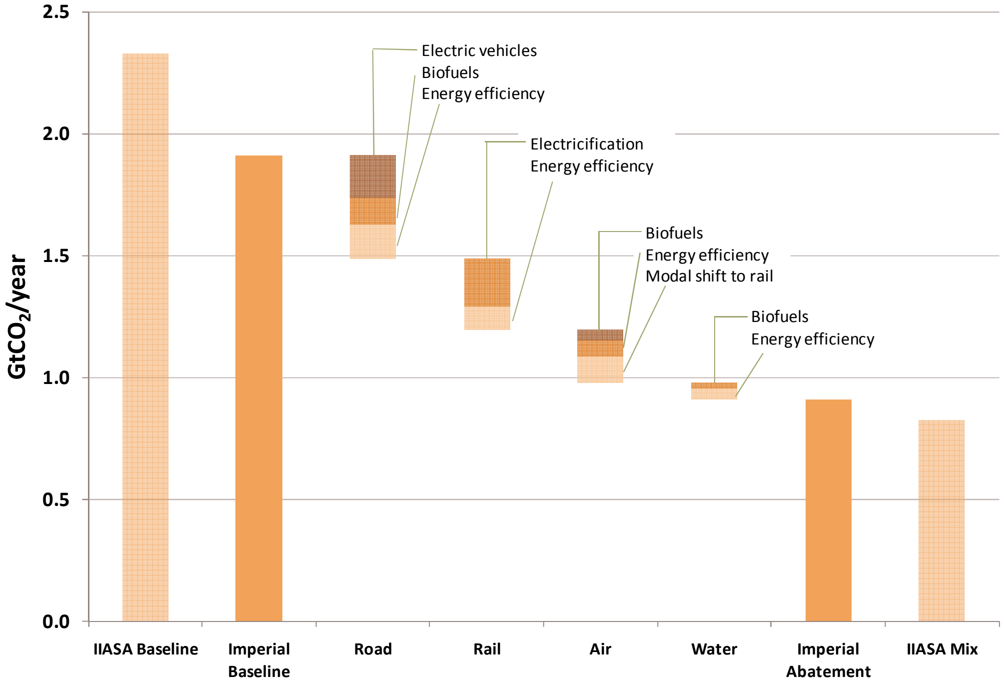
[15] Source for historical data: Dr. Lee Schipper, Global Metropolitan Studies, UC Berkeley

by transport mode, and electrification (of rail and road) combined with decarbonisation of electricity makes up the majority of overall savings. The Figure also shows that Imperial's Baseline scenario has lower emissions by 2050 compared to IIASA's. This is in part a result of the Imperial model referring to China rather than the (approximately 10% larger) CPA region of IIASA's modelling, and is also likely to be the result of Imperial's business as usual assumptions having greater levels of energy efficiency than IIASA's.

Figure 5.5: 2050 transport emissions savings in Imperial abatement scenario, by measure



5.9 Table 5.1 discusses the challenges presented by scaling up these technologies, with further details of electric vehicles and biofuels given in Annex D. There are currently several challenges to achieving emissions savings from electric vehicles in China, including bringing down battery costs, constructing an electric charging infrastructure, and of course decarbonising the electricity grid. China is already seeking partnerships with a number of overseas car companies to improve its own technological capabilities in vehicle manufacture. In addition, the planning challenges for charging infrastructures that several countries now face create an opportunity for international collaboration. A number of significant abatement options, notably energy efficiency in non-road sectors, are based on relatively crude assumptions on the continuation of historic efficiency trends, and would benefit from further research.

Table 5.1: Summary of abatement options in the Chinese transport sector

Technology		2050 abatement potential (Gt CO_2)	Abatement cost range*	Status of technology in China/ abroad	Key challenges to scale-up to 2050 levels
Road	Electric vehicles	0.17	High	• Early stage of commercialisation • Extensive experience in China of manufacturing 2-wheeler electric vehicles	• Carbon savings rely on decarbonised grid; • Lack of charging infrastructure though regional plans are emerging; • Battery energy density, cost, and production resource/energy intensity improvements required • China does not own valuable IP in many EV technology areas; • Customers aim for luxury and comfort over electric vehicle technology; • Remaining oil subsidies keep petrol prices lower; • Battery and component production highly resource and energy-intensive.
	Biofuels	0.11	Uncertain	• Second generation biofuels are yet to be commercialised.	• Potential lack of reliable , sustainable feedstock - importance of setting and monitoring standards to ensure this;
	Efficiency	0.14	Low	• Current standard of 7.9 km/l fleet average fuel economy is the third most stringent in the world, after Japan and the EU;	• Savings depend on the degree of rebound effect (i.e. increased driving as a result of higher fuel economy); • Potential increase in larger, high-emission vehicles with improving in living standards.
Air	Modal shift to rail transport	0.11	Low	• Competition from high-speed rail already impacting domestic air transport demand forecasts [34].	• Above 800 km, air option is likely to be faster in terms of overall door-to-door journey time [35]
	Biofuels	0.04	Uncertain	• Air China Ltd. Is in cooperation with Boeing Co. to test a commercial- jet biofuel in China produced from a locally grown plant by the middle of 2011 [36].	• Competition of biofuels with road, water transport sectors; • Technology breakthroughs are required to commercialize 2nd, 3rd generation biofuels [35].
	Efficiency	0.06	Medium	• Evolutionary technology innovation could lead to fuel efficiency improvements in new aircraft of the order 35-45% by 2025 [35]	• Technologies to achieve further efficiency improvements (up to 60% by 2050) are more speculative and require R&D [35] • Air traffic management efficiency faces several challenges including safety and noise pollution [35].
Water	Biofuels	0.02	Uncertain	• There have been a limited number of projects using biofuels in ships [37].	• Competition of use of biofuels with aviation and road transport sectors.
	Efficiency	0.04	Low to medium	• Domestic corporations such as China Shipbuilding Industry Corporation (CSIC) are optimizing shapes to reduce friction and routes to improve marine transportation efficiency.	
Rail	Electric	0.19	High	• Electrified share of rail transport in China in 2008 is 32.7% [38].	• Carbon savings rely on decarbonised grid.
	Efficiency	0.10	Low to medium	• Several domestic companies such as CSR Corporation Ltd. are building trains with improved technologies including advanced engines and air brake systems.	

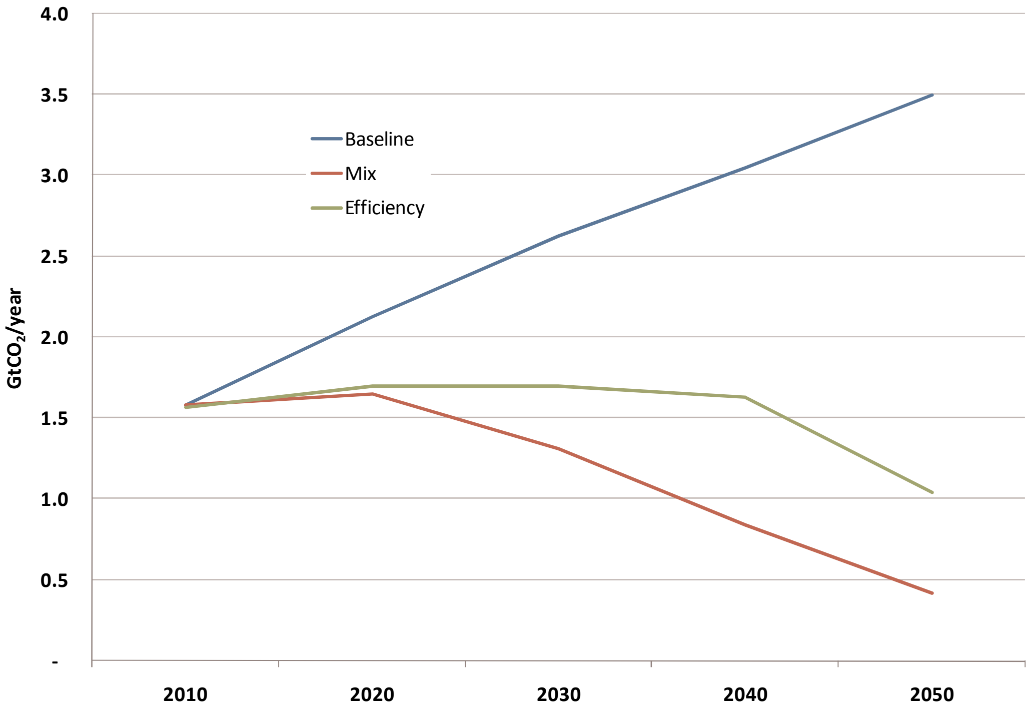
Notes: *Low Cost = \$0-50/tCO_2; Medium Cost = \$50-100/tCO_2; High Cost = over \$100/tCO_2, using Imperial judgements based on a range of sources (see Annex E)

6 Buildings

6.1 Emissions from the residential and commercial buildings sector (including electricity) made up about 20% of total CO_2 emissions in 2008 [39]. This is a smaller share than OECD countries where buildings account for closer to 40% of total CO_2 emissions[16] – in part this is a result of the dominance of industry in China's emissions mix, but it also reflects the smaller number of appliances per household, the widespread use of biomass in rural areas, and the lack of adequate heating facilities (for both space and water heating) in many households [40]. Although typical lifetimes of buildings in China are around 25-30 years [41] the rapid growth of urban population and the associated demand for residential and commercial buildings indicate that it is important that China does not lock into a high-carbon pathway in the sector over the next few decades[17].

6.2 IIASA's Baseline scenario projects emissions from buildings will be 3.5 $GtCO_2$ in the CPA region by 2050, about 21% of total CO_2 emissions in the region. It is projected that buildings will emit 0.4 (Mix) - 1.1 (Efficiency) $GtCO_2$ in 2050 in the IIASA abatement scenarios, 19% of total CO_2 emissions in the Mix scenario and 23% in the Efficiency scenario. Figure 6.1 shows the emissions in each IIASA abatement scenario relative to the Baseline.

Figure 6.1 Buildings emissions in the IIASA Baseline and abatement scenarios



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[16] Care should be taken with this comparison as different countries can have different classifications for heating and lighting (e.g. in factories and warehouses, where these services can be alternatively assigned to industry or commercial building energy use).

[17] Although not assessed in this study, from a Life Cycle Analysis viewpoint, energy and emissions embodied in buildings should also considered, as this could represent a significant contribution ([39], [42]).

6.3 There are a number of uncertainties about data in the Chinese buildings sector. Biomass is the predominant fuel in rural households, but sources vary greatly on the amount being employed in these areas or the efficiency of end-use conversion technologies. Data is also scarce in the commercial sector, where detail on floor space and fuel consumption by end-use is difficult to obtain outside of China.

6.4 IIASA's energy demand modelling for buildings assumes a high penetration of Passivhaus standard housing, and a large-scale shift from biomass and other low-quality fuels towards electricity and natural gas, but does not state explicitly the mix of technologies that will in combination lead to the level and mix of final energy demands. Imperial has therefore developed a bottom-up model of the buildings sector in China to assess in greater detail the technology mix in an abatement scenario. The modelling methodology is described in detail in Annex C, but the key assumptions are as follows:

- **Buildings growth:** Growth in the sector is driven by household habitation (persons per household) as a function of GDP per capita in urban and rural residences, and commercial floor space as a function of service sector value added;
- **Heating and cooling demands:** The model subdivides China into three regions – a cold, Northern region where district heating is the dominant heat supply technology [43]; a Transition region with cooling and higher penetration of electric resistive heating ('Yangtse' region); and a Southern cooling/dehumidification region;
- **Electricity:** the carbon intensity is assumed to be that of the IIASA Mix abatement scenario.

6.5 Figure 6.2 shows the energy demand comparison between the Imperial and IIASA abatement scenarios. Overall energy demand in the Imperial model is for most years higher than the IIASA Mix and Efficiency levels, although in 2050 it is between the IIASA abatement scenarios, and very similar to the IEA's (2010) Energy Technology Perspectives (BLUE Map) low-carbon projections. The Imperial scenario projects continued use of biomass throughout the period to 2050, albeit with vastly increased efficiencies due to high efficiency conversion technologies and a shift towards commercial sources, whereas this is assumed to be completely phased out by 2050 in both IIASA scenarios. All scenarios show a reduced dependence on coal (which is rapidly phased out in the IIASA scenarios) and oil, with an increase in gas demand.

6.6 As shown in Figure 6.3, Imperial's scenario, as a result of higher biomass usage, has lower emissions than both the IIASA scenarios throughout the period to 2050, with emissions levels very similar to the IIASA Mix scenario from 2030. The Imperial analysis therefore suggests that more aggressive emissions savings are possible in the early decades, but this is heavily reliant on the assumptions that biomass emissions would be zero (i.e. that biomass heating and cooking is from genuinely renewable sources). The IEA's BLUE Map emissions for 2050 are higher than in the Imperial scenario, as the assumed electricity CO_2 intensity is higher (121 gCO_2/kWh) than the Imperial level of below 50 gCO_2/kWh (based on IIASA's Mix scenario) by 2050.

Figure 6.2 Buildings energy demand comparison between Imperial and IIASA abatement scenarios

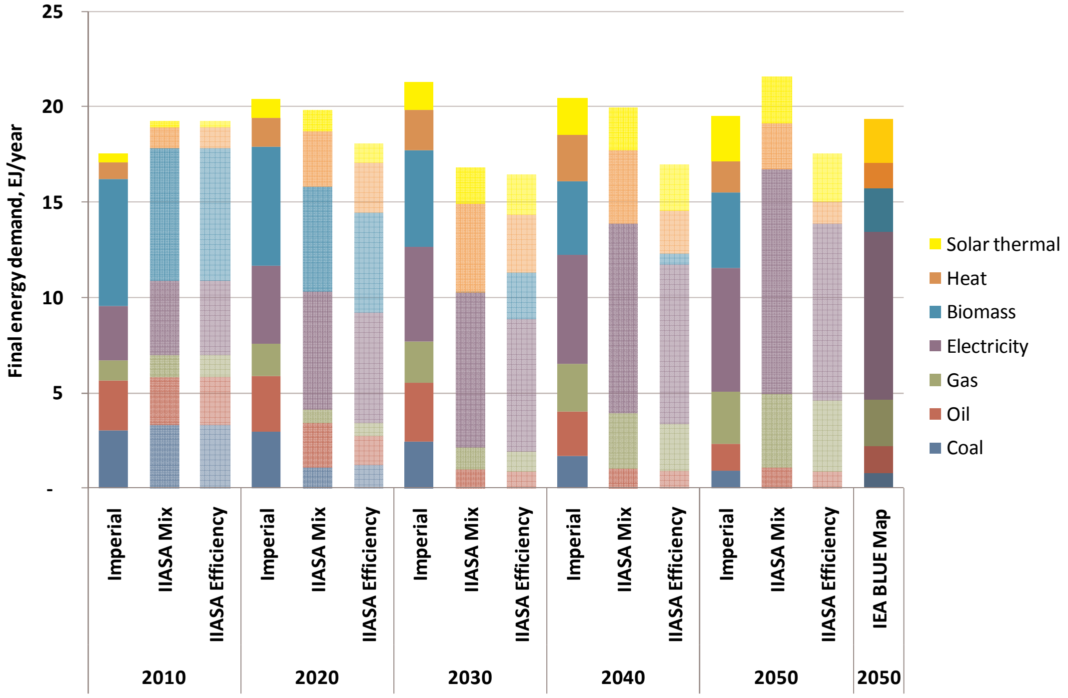
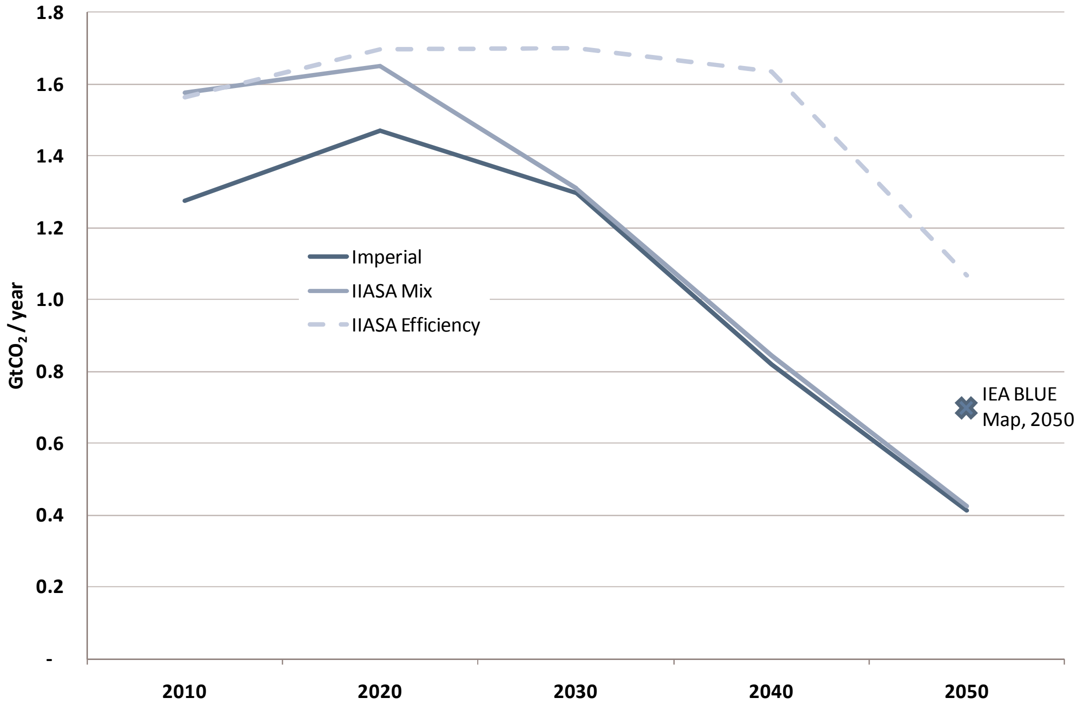
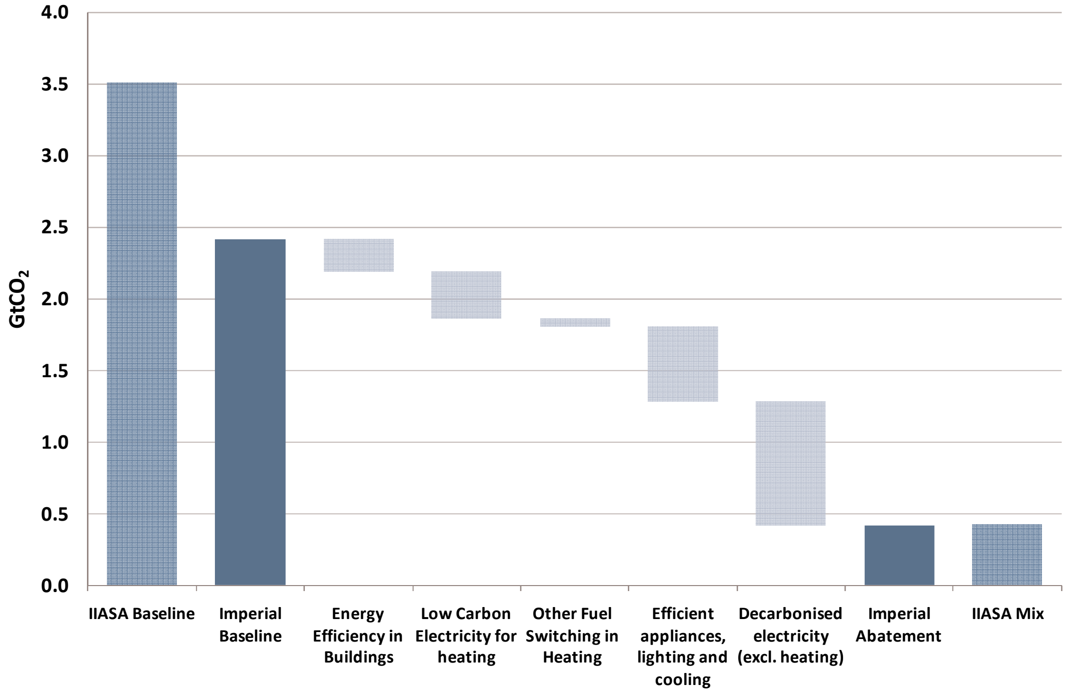


Figure 6.3 Buildings emissions comparison between Imperial and IIASA abatement scenarios



6.7 Figure 6.4 shows the major emissions saving options and measures in the Imperial abatement scenario, with the IIASA Baseline and Mix scenarios shown for comparison. The key mitigation options in the Imperial abatement scenario are efficiency of lighting, appliance and cooling equipment, and the decarbonisation of electricity used by this equipment. Additional key abatement options include low carbon electricity for heating (essentially heat pumps, which achieve a particularly high penetration in the transition areas); and an expansion and increased operational efficiency of district heating schemes in Northern areas, supplied by advanced heating technologies (e.g. Fuel Cell CHP).

Figure 6.4 2050 emissions savings in Imperial abatement scenario, by sector and measure



6.8 The Imperial Baseline scenario has significantly lower emissions in 2050 than the IIASA Baseline. A number of different studies assume varying levels of efficiency improvements in the Baseline, with for example the IEA (2010) Energy Technology Perspectives and IIASA's own Baseline assuming a more "frozen" level of technology, and little efficiency improvement. By contrast, Lawrence Berkley National Laboratory [44] and Imperial's own modelling assumes that, as the Chinese building stock grows, newer, more efficient technologies with higher levels of efficiency are implemented. This is arguably a more realistic assumption given historical developments.

6.9 The key challenges to scaling up the abatement measures are outlined in Table 6.1, and discussed in further detail in Annex D. In the Imperial abatement scenario, building envelope efficiency reaches, on average, a level which is consistent with the Carbon Trust/AECB Silver Standard (40 kWh/m^2 for heating). This is more ambitious than the levels of energy efficient building envelope assumed in the IEA BLUE Map scenario, but less so than IIASA's high penetration of Passivhaus-standard housing (15-30 kWh/m^2). This would require not only close agreement and coordination between regional and central governments, but a highly accelerated ramp-up of institutional capabilities to draft, enforce and monitor ambitious building codes before 2020.

6.10 A high seasonal Coefficient of Performance (CoP) of 4 has been assumed for heat pumps in 2050, which is comparable to current Japanese best practice[18]. However poor heat pump installation and operation can lead to lower CoP values and it is assumed that peak demand is met by resistive (and thus lower CoP) heating in an optimised package. As a result, the savings from the large-scale roll-out of heat pumps envisaged here would require a co-incident push for conservation measures and training, monitoring and awareness programmes.

6.11 Similarly, a continued increase in appliance efficiency is assumed which would require the Chinese appliance stock to reach efficiency levels comparable to Japanese best practice standards of ten years ago, a near-doubling of efficiency across the main appliance categories. This would require ambitious new regulation and strict labelling, testing and monitoring of appliances.

6.12 Overall the challenges to decarbonising the buildings sector are characterised not by the development of new technologies (most of which already exist, and which are in use in different regions of the world), but by the requirement to ensure that strict standards for efficiency and the use of low-carbon technologies are enforced. As a number of other countries face a similar challenge of implementing (in many cases low cost or even negative cost) energy efficiency and low-carbon buildings measures, there are likely to be numerous opportunities for collaboration with China in this area.

6.13 The Imperial modelling currently assumes a largely uncoordinated urban land use development, and does not differentiate rates of urbanisation in different regions. It therefore does not reflect the energy and CO_2 savings potential across different sectors arising from integrated urban planning. In addition, projecting energy demand for commercial buildings is problematic: the efficiency of commercial services per square metre is constantly increasing, and there are significant uncertainties around the level of future demand per square metre. Some sensitivities around residential and commercial floor space are discussed in Section 7: Total emissions savings, of this study, but further consideration of the factors driving energy usage would be beneficial.

6.14 Other areas for future research include: gaining a better understanding of stock turnover rates which would allow for more detailed modelling of retrofits, as many Chinese policies apply only to new build; further detail on the potential for different technologies in water heating and cooking; and obtaining improved estimates on biomass usage.

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[18] This assumes adequate sizing of heat pumps to match demand

Table 6.1 Summary of abatement options in the Chinese buildings sector

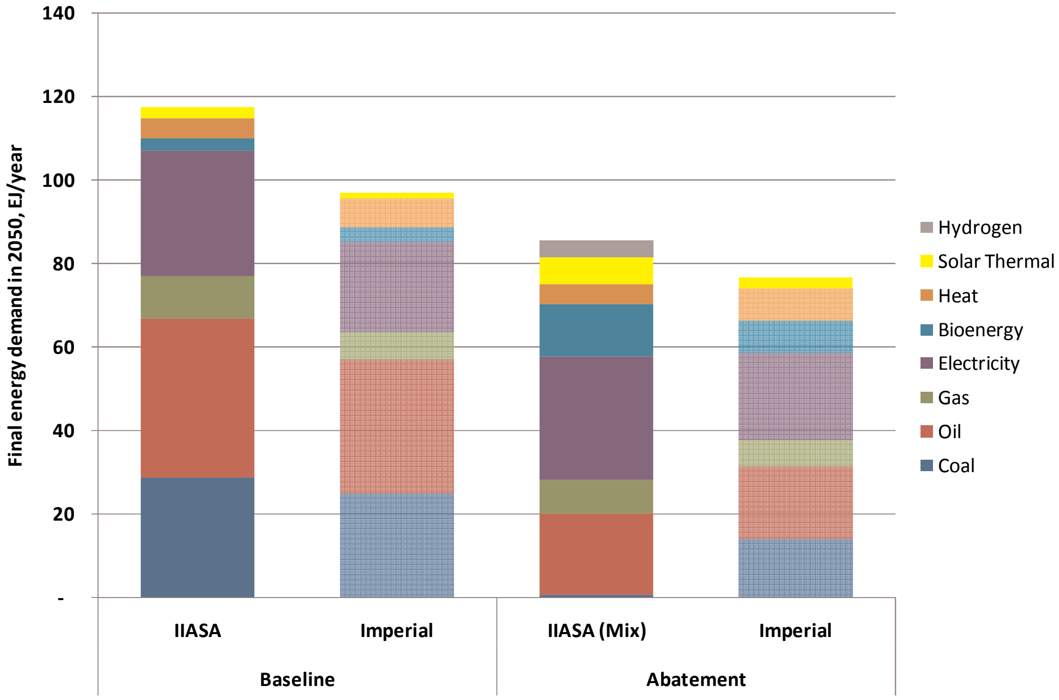
Technology	2050 abatement potential ($GtCO_2$)	Abatement cost range*	Status of technology in China/ abroad	Key challenges to scale-up to 2050 levels
Low carbon heating (CHP, heat pumps and solar thermal)	0.53	Negative to Low	• Mature in China and elsewhere; High penetrations in Northern and Central Europe; • Support for large-scale heating installations, small-scale CHP non-existent; • Depending on technology and application, pre-commercial /early-stage commercial.	• District Heating schemes are operated inefficiently (billing practices not based on actual consumption, leading to high rebound effects); • Innovation and institutional capacity with regard to financing is necessary; • General lack of exposure to energy and CO_2-saving technologies among developers, government, etc; • Lack of accredited installers and institutional capacity; • The degree to which traditional biomass will be phased out and the marginal technology that will substitute it present key uncertainties; • Generous subsidies for coal – lower costs for incumbent technology.
Lighting, cooling and appliances	1.24 (of which 0.87 from electricity decarbon-isation)	Negative to low	• LEDs for residential lighting are early stage, CFLs are commercial and widespread in China; • Other technologies largely commercial.	• Institutional capability requires accelerated ramping up; monitoring, implementation, and ambitious regulation will be necessary to ensure the savings potential is achieved; • Highly fragmented markets for many appliances increase difficulty of regulation and monitoring [45]; • Strong industry lobbying has stalled the growth of the green appliance market (e.g. delayed, weak AC standards).
Energy efficiency in buildings	0.23	Negative to low	• Established standards in Northern and Central Europe; but currently low penetration of low-carbon housing in China.	• Different climate zones require regional policies and targets, which present barriers for monitoring and implementation; • Challenging to achieve effective implementation of standards given potentially competing regional economic development objectives; • Growth in building stock too high, standards unable to keep up; • Principal-agent issues, particularly in the commercial sector [46].

Notes: *Low Cost = \$0-50/tCO_2; Medium Cost = \$50-100/tCO_2; High Cost = over \$100/tCO_2, using Imperial judgements based on a range of sources (see Annex E)

7 Total emissions savings in the IIASA and Imperial scenarios

7.1 Combining the analysis for the industry, transport and buildings sectors allows a comparison of the projected savings in the Imperial Abatement scenario. Figure 7.1 shows the energy demand (by fuel type) in 2050 in the Imperial Baseline and Abatement scenarios, as compared to the IIASA Baseline and Mix scenarios.

Figure 7.1: Final energy demand in the Imperial and IIASA Baseline and Abatement scenarios



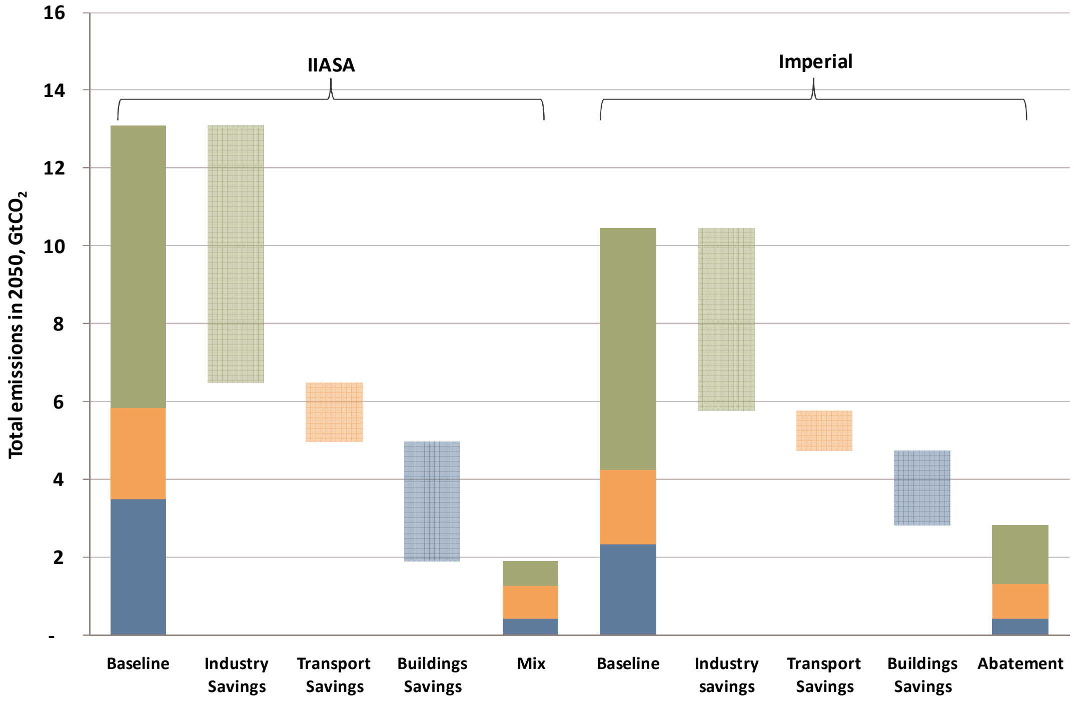
7.2 In general the energy demand projected by the Imperial scenarios is lower than that in the IIASA scenarios, for the both the Baseline (17% lower) and Abatement (11% lower) scenarios. For the Baseline this partly reflects the greater energy efficiency improvements assumed in Imperial's business-as-usual projections, whilst for both the Baseline and the Abatement scenarios the Imperial projections are lower as they are for China alone rather than the (approximately 10% larger in GDP and population terms) CPA region. Hence the Imperial modelling provides a useful sanity-check for the levels of end-use final energy demand which have been used in the IIASA modelling, which in total seem reasonable.

7.3 It is worth noting that the composition of energy demand is rather different in the two abatement scenarios shown in Figure 7.1 - there is far more coal in the Imperial abatement scenario relative to the IIASA Mix scenario, and about 10 EJ/year less electricity demand. Coal demand is higher principally because IIASA assume a range of substitutes (including biomass) for coal used as a feedstock in the industry sector, whereas Imperial's modelling is more conservative and assumes that, by 2050 at least, there will be relatively limited opportunities to replace coal as a feedstock in non-metallic minerals and iron & steel production, as discussed in Section 4: Industry sector. The greatest difference in electricity demand is in the buildings sector, where IIASA's modelling shows a much greater use of electricity in lighting, appliance and cooling compared to Imperial's modelling. This could be the result of less aggressive assumptions by IIASA on the energy efficiency improvements of this electrical equipment, where Imperial's research indicates significant potential.

7.4 As shown in Figure 7.2, the higher coal demand in the industry sector in the Imperial abatement scenario contributes to higher overall emissions compared to the IIASA Mix scenario. However, overall savings are lower across all sectors: in transport the IIASA Mix scenario has a slightly lower oil demand than the Imperial abatement scenario, but the total savings are principally lower due to the fact that the emissions in the Imperial Baseline scenario are lower than in the IIASA Baseline scenario. In the buildings this is also true. In addition, in the buildings sector the savings resulting from the greater electrification in the IIASA Mix abatement scenario and lower reliance on coal and oil relative to the Imperial abatement scenario mean that the Imperial abatement scenario shows smaller emission savings compared to the IIASA Mix scenario.

7.5 Nevertheless, the IIASA and Imperial scenarios report a broadly similar message – that the greatest abatement opportunities come from the industry sector (principally through electrification) and that emissions from these end-use sectors (which includes electricity emissions) could be reduced to below 3 $GtCO_2$ in China by 2050, based on the assumptions used in the Imperial modelling for the end-use sectors, combined with IIASA's projections for electricity decarbonisation as given in the Mix scenario.

Figure 7.2: Comparison of emissions savings in Imperial and IIASA abatement scenarios by 2050



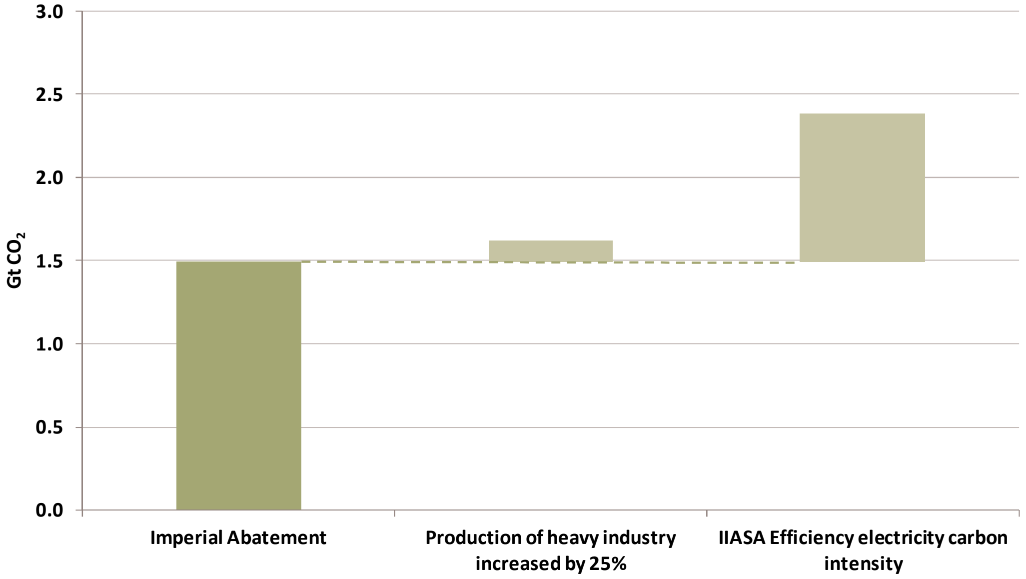
Notes: Emissions do not include energy conversion emissions, which are 2.8 $GtCO_2$ in the IIASA Baseline and 0.4 $GtCO_2$ in the IIASA Mix scenario by 2050. Imperial analysis does not consider the energy conversion sector.

7.6 It should be noted that the emissions shown in Figure 7.1 do not include emissions from the energy conversion sector, which in the IIASA Baseline scenario are 2.8 $GtCO_2$, and in the IIASA Mix scenario are about 0.4 $GtCO_2$, by 2050.

7.7 There are a wide range of uncertainties when projecting to 2050. Annex A shows that IIASA's scenarios are on the low side in terms of overall GDP growth between 2010 and 2050, so it is worth considering the emissions impact of, amongst other factors, greater activity levels in key emitting sectors.

7.8 For example, in the industry sector, it is unclear the degree to which China will have transitioned away from heavy (energy-intensive) industry. In addition, the Imperial abatement scenario uses IIASA's Mix scenario's electricity CO_2 intensity value, where electricity becomes highly decarbonised (below 50 gCO_2/kWh) by 2050. Figure 7.3 illustrates how industrial emissions (including indirect emissions from electricity) would change if these assumptions were changed. With heavy industrial production increased by 25%, overall industry emissions would increase by about 0.1 $GtCO_2$ by 2050. Using the IIASA Efficiency scenario's electricity CO_2 intensity (280 g/kWh by 2050), overall industry emissions would increase by about 0.9 $GtCO_2$ by 2050.

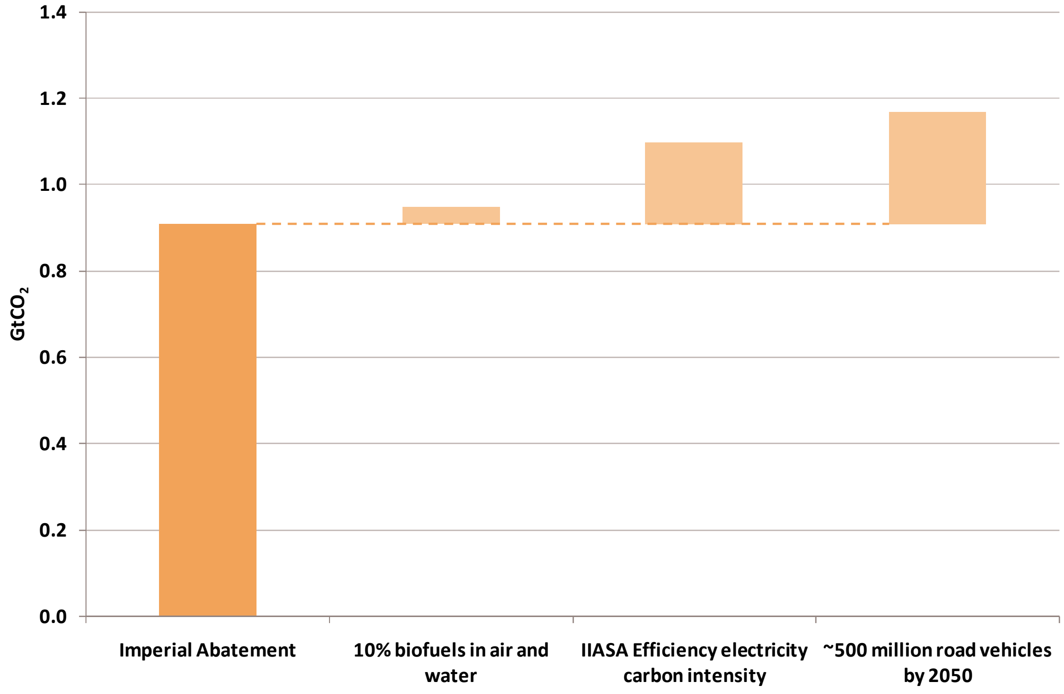
Figure 7.3: 2050 industry CO_2 emissions in Imperial abatement scenario with sensitivity analysis



7.9 In the transport sector, key uncertainties in the modelling include the degree to which biofuels might replace oil products in the air and water transport sectors[19], the electricity CO_2 intensity, and the road vehicle stock by 2050. Figure 7.4 illustrates how variations in these assumptions would change overall transport emissions by 2050. The most significant increase in emissions would result from an assumption that China has about 500 million road vehicles by 2050 (in line with the assumption by Ou et al [33]), rather than just over 300 million, as assumed in the Imperial model. This higher vehicle stock would result in an additional 0.3 $GtCO_2$ emissions by 2050.

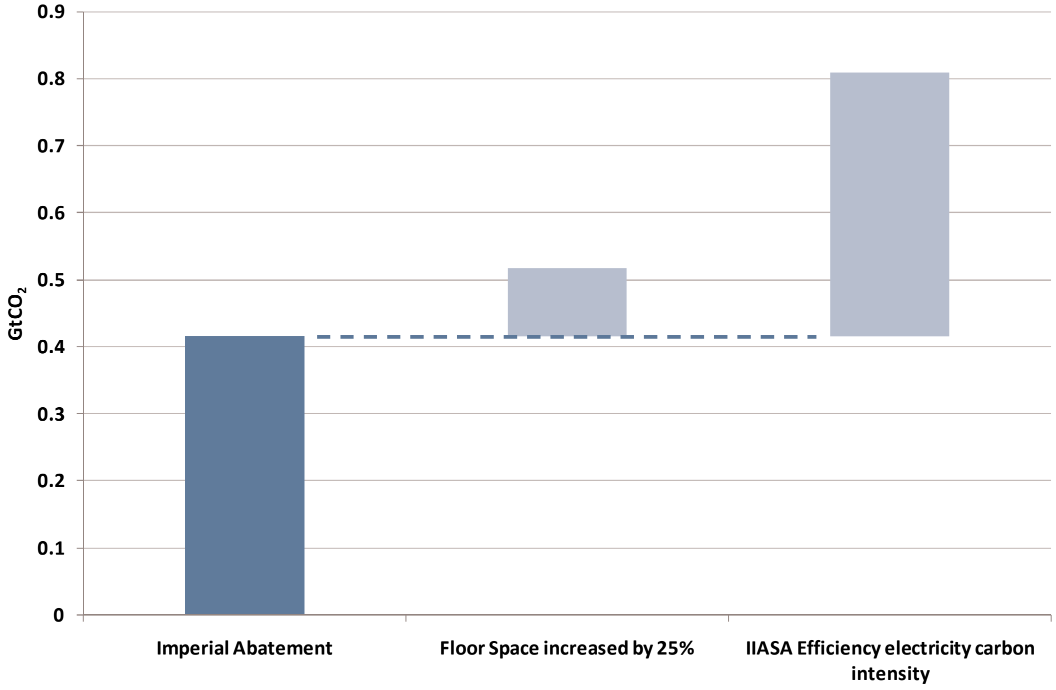
[19] Although the assumptions used in the Imperial modelling (20-30% biofuels in water and air transport by 2050) broadly agree with the IEA's (2010) Energy Technology perspectives [1], reviewers at Tsinghua University have commented that this may be optimistic.

Figure 7.4: 2050 transport CO_2 emissions in Imperial abatement scenario with sensitivity analysis



7.10 Figure 7.5 illustrates the impact of a 25% higher assumed level of residential and commercial floor space by 2050, with associated increases in energy service demand, and also the impact of a higher CO_2 intensity of electricity. Emissions would increase broadly in line with floor space, whilst using IIASA's Efficiency scenario's electricity CO_2 intensity almost doubles overall buildings emissions, as there is significant electrification of all buildings energy services by 2050.

Figure 7.5: 2050 buildings CO_2 emissions in Imperial abatement scenario with sensitivity analysis



7.11 The overall impact of the higher electricity CO_2 assumption is to add about 1.5 $GtCO_2$ to 2050 emissions, about a 50% increase on the Imperial Abatement scenario, underlining the importance of achieving a highly decarbonised electricity generation system by 2050.

8 Cross cutting issues

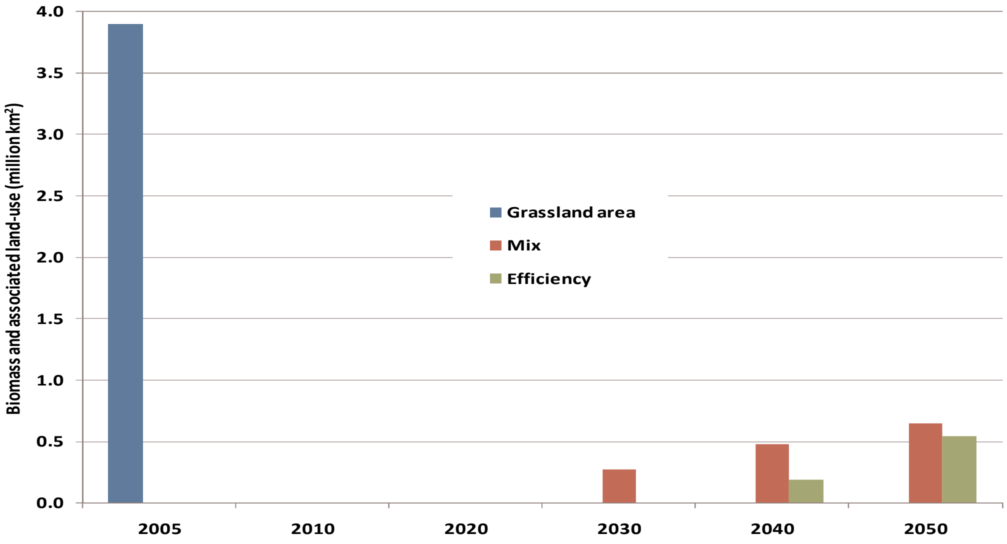
8.1 China's low carbon development pathway would see the deployment of a range of new technologies, which in combination will have different resource use implications to more carbon intensive technologies. In this section the specific implications for land and water usage, fossil fuel and uranium resource usage, and spatial network planning are considered.

LAND USAGE

8.2 As of November 2005, China's arable land amounted to 0.27 hectares per capita, less than 40% of the world average. In the East of the country, high quality arable land is being lost to construction, while in the West low-quality arable lands have been appropriated for forest or grassland re-planting efforts. Shrinking arable land, combined with population growth, has led to rising concerns about food security [47]. Significant efforts have been made to increase forest coverage, which has been increased from 1.15 million km^2 in 1980 to 1.73 million km^2 in 2009. China's National Climate Change Programme has outlined plans to increase forest coverage further to 2.13 million km^2 by 2020 in accordance with the UN Framework Convention on Climate Change [48]. It should be noted however that non-native species, such as the vast rubber plantations in southern Yunnan, are included in this definition of forest [49] .

8.3 The IIASA abatement scenarios do not envisage any significant net increase in bio-energy by 2050, but traditional biomass (used largely for residential heating and cooking) is phased out and replaced with an increase in biofuels for transport and biomass energy for industry. Total biomass for primary energy use remains in the region of 8 EJ/year. Figure 8.1 shows, however, that there is considerable potential for further increasing the contribution of biomass, provided that a greater share of China's extensive grasslands could be brought into play.

Figure 8.1: Land-use implications of purpose grown biomass in the CPA region [48], [50]



8.4 Using grasslands for biomass production is closely linked to the development of second generation "cellulosic" biofuel technology, making it possible to use a wider variety of biomass sources, including fast-growing grasses or trees, crop or forest residues, and even paper waste. However, the transport of such energy sources, as well as other constraints such as nutrient and water management (which could to a large extent depend on the effects of climate change), are likely to be challenges in this area.

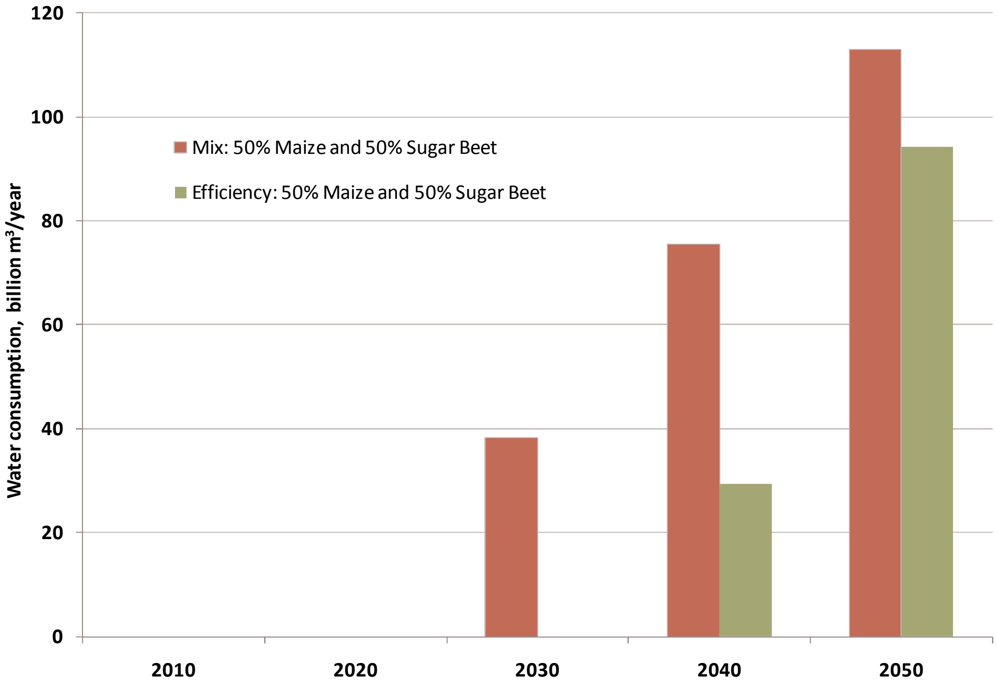
WATER USAGE

8.5 China's annual total renewable freshwater has been estimated at 2100 billion m^3 [51] (although its total water resource base may be as high as 3500 billion m^3 [52]). Approximately 470 billion m^3 of water per year is withdrawn for use in agriculture (67%), industry (26%) and domestic applications (7%). Industrial demand is largely driven by water withdrawal and consumption for thermal power generation. Water withdrawal can be defined as "water removed from the ground or diverted from a surface-water source for use" whilst water consumption is "the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" [53]. The analysis below focuses on the water resource impact of biomass production and electricity generation, although the impact of water demand from coal-to-liquids technologies and non-electricity uses of CCS for instance may also prove significant.

8.6 China faces the prospect of increasing pressure on water resources, with a severe shortfall in some of the most highly industrialised parts of the country and a moderate gap in many other regions. Overall water demand in agriculture is projected to be over 400 billion m^3 by 2030 (assuming a static policy regime and existing levels of efficiency and productivity), but industry and power generation could demand over 250 billion m^3 [52]. There may be a range of impacts on water supply in western China as a result of climate change, as a result of earlier spring snowmelt and declining glaciers [54]. The 'North to South Water Transfer' is one example of an immense infrastructure project seeking to transfer water from the southern Yangtze river to the industrial north [51].

8.7 Purpose grown biomass could have considerable additional water requirements. Figure 8.2 shows various estimates of the biomass water requirements of the Efficiency and Mix scenarios, based on international experience with different crops. While the ranges between different examples are very large, the scale of water demand suggests that water will be an important factor in China's choice of biomass options.

Figure 8.2: Estimated water consumption of purpose grown biomass in the CPA region [55]



Notes: There is a wide range of values for water usage reported in the literature, with some attributing no increase in pressure on water resources to increased biomass production (EC 2005 Biomass Action Plan) whilst others account for the water footprint, defined as: "The volume of fresh water used for the production of that product at the place where it was actually produced" [56].

8.8 Figure 8.3 shows the volumes of water consumed[20] annually in power generation in the IIASA abatement scenarios. The totals in 2030 are in the region of 2% of China's total water demand, as estimated by the Water Resources Group (2010). However the impact in specific locations where water is scarce could be significant. The Figure shows hydro, where water evaporation is an issue, as much the largest consumer of water, with most of the remainder consumed in coal power stations, and then in nuclear stations as the nuclear programme grows. Whilst in aggregate the additional water consumption is small compared to water used in bio-energy production, local water availability will be an important consideration for the location of particular generation plants.

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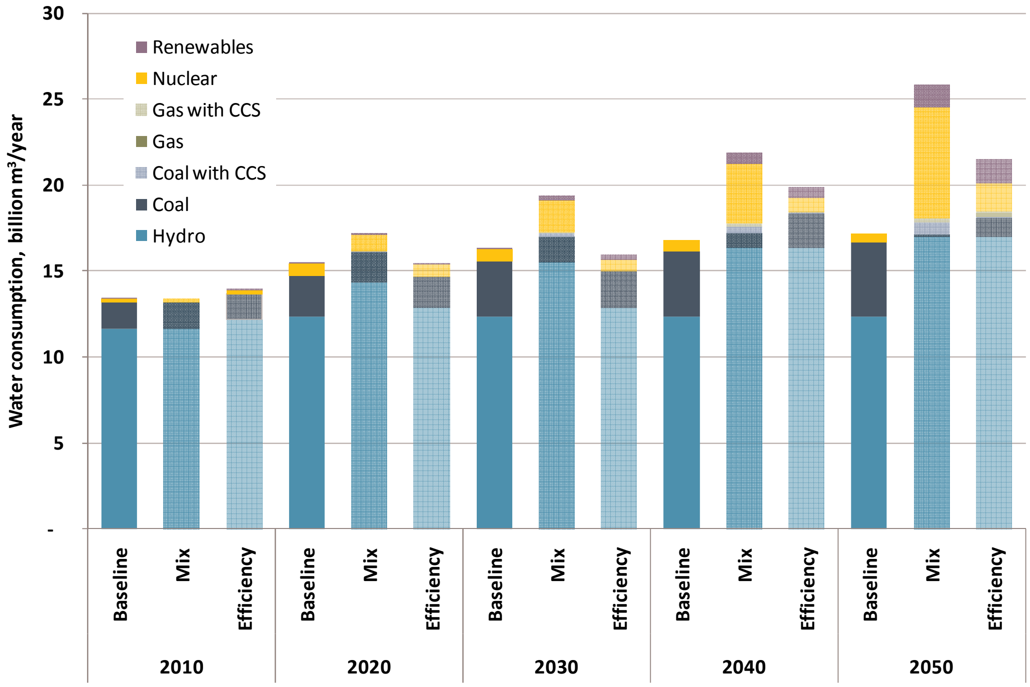
[20] Water withdrawal is also an important issue to consider besides water consumption. It is roughly ten times higher than the water consumption rate of coal power in China.

Figure 8.3: Water consumption in the power sector in CPA, by generation technology [55]



Notes: Assumed power generation types for water consumption calculations; Sub and super critical coal once through cooling cycle, IGCC wet tower, IGCC with CCS wet tower, nuclear wet tower PWR, Oil once-through, gas once-through, gas with CCS wet tower, solar thermal wet cooling.

OIL DEMAND

8.9 China's oil reserves stand at an estimated 14.8 billion barrels[21], about half those of the US and 6% of Saudi Arabia, and equivalent to 11 years of current production [57]. In view of the assumed continuing growth of the economy as a whole, all of the IIASA scenarios imply increasing oil demand to 2030, but with decreasing demand in the abatement scenarios thereafter, as shown in Table 8.2. To set these figures in context, China's domestic oil production is expected to stabilise at its current (2009) level of about 4 million b/d [43], and is unlikely to increase beyond that in the future. Hence demand will outstrip domestic production throughout the period to 2050 in all three scenarios, indicating that China will continue to be reliant on imports.

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[21] It is worth noting that this figure has not changed in recent years despite significant increases in oil demand in China, so should be treated with caution.

Table 8.2: Projected oil demand in the CPA region for the IIASA Baseline and abatement scenarios

IIASA scenario	Primary oil demand, million b/d				
	2010	**2020**	**2030**	**2040**	**2050**
Baseline	8.3	12.0	13.7	17.0	16.1
Mix	8.3	12.2	13.3	13.1	7.3
Efficiency	8.3	9.7	11.1	12.3	9.4

8.10 China's major oil companies have engaged in a vigorous programme of investment and political engagement to access international oil reserves. For example, from October 2008 to December 2009 the major Chinese national oil companies invested nearly $17 billion for direct acquisition of international oil and gas assets, whilst the Chinese government finalised loan for oil deals recently with Russia, Brazil, Venezuela, Kazakhstan, Ecuador, and Turkmenistan. Oil from eastern Russia and Turkmenistan would be delivered through major new pipeline projects [8]. Annex F includes analysis of the regions and countries that exported oil to China in 2009. It is clear that the Middle East, western Africa and other major exporters to China will begin catering much more so for their Asian customers in the longer term [58].

8.11 China National Petroleum Corporation (CNPC) plans to spend $60 billion to expand overseas production to 4 million b/d by 2020 [8]. This expansion seems likely to continue as China's National Oil Companies (NOCs) seek to acquire new reserves to replace their used-up oil wells [59]. On IIASA's projections for China's domestic production this could approximately meet China's oil import needs, although on the IEA's less optimistic forecasts only about half of China's imports would be covered by this CNPC production. In any case, as has been demonstrated on many occasions, international commercial and political agreements do not always guarantee either the availability or the price of oil in times of crisis.

8.12 In principle, coal-to-liquids technology, which has been demonstrated in China, represents another option for meeting oil demand. However this may be restricted by water supplies, with 1 tonne of coal-to-liquids fuel requiring 10 tonnes of water input [9]. For China, therefore, growing oil import dependency represents a serious strategic and economic concern, and a strong reason, in addition to environmental considerations, for adopting oil conserving measures such as those in IIASA's Mix and Efficiency scenarios, which by 2050 would approximately halve primary oil demand relative to the Baseline.

GAS DEMAND

8.13 China's conventional natural gas reserves stand at 2.46 trillion cubic metres (about a third of US reserves, 6% of Russia, and 1.3% of global reserves), representing 29 years of current production [57]. However, recoverable reserves of unconventional gas, such as coal bed methane (CBM) and shale gas may be more than three times conventional reserves [8]. In fact a recent US Energy Information Administration (EIA) study suggests that China's technically recoverable shale gas could be about 36 trillion cubic metres, over ten times conventional natural gas reserves [60].

8.14 In the IIASA Mix scenario, the share of gas in primary energy demand increases from 4% in 2010 to 22% in 2050, by which time gas has become China's second largest source of primary energy, only exceeded by coal. Most of this gas is expected by IIASA to come from domestic sources, with 14% supplied by imports in 2050. In contrast, the IEA (World Energy Outlook [7], Tables 5.2 and 5.4) expects that China will be importing more than half its gas supply by 2035, most likely from LNG/pipeline imports and unconventional gas (such as shale gas).

Table 8.3: Projected gas demand in the CPA region for the IIASA Baseline and abatement scenarios

IIASA scenario	**Primary gas demand, billion cubic metres / year**				
	2010	**2020**	**2030**	**2040**	**2050**
Baseline	97.9	98.5	133	252	385
Mix	97.9	117	213	507	747
Efficiency	97.5	99.0	133	236	456

8.15 In the IIASA Mix scenario, there is a progressive increase in the share of domestic production coming from unconventional sources, which contribute more than half of total production by 2040. The CNPC has entered into joint ventures with a number of international companies to develop unconventional gas resources and China signed an agreement with the US in November 2009 to co-operate on shale-gas development.

8.16 China is also engaged in major efforts to expand its gas infrastructure, in terms of pipelines and LNG import terminals to access international supplies. The IEA (World Energy Outlook [7], Table 5.6) estimates that China will spend $132 billion on gas transmission and distribution and 48 billion on LNG facilities between 2010 and 2035. Of China's 210 bcm of gas imports in 2035, 44 bcm would come from LNG shipments and the remainder by pipeline largely from Russia and the Caspian region. China has eight LNG reception projects under construction, all of which are due to be commissioned by 2015, adding 77 bcm to current capacity of around 360 bcm. Close to 30% of this increase will come from Qatar. Other suppliers are expected to include Algeria, Angola, Australia, and Papua New Guinea.

8.17 The extent of the contribution of gas to China's future energy mix is very uncertain. It depends on China's success in following the example of the US in developing unconventional gas reserves, on international negotiations for pipeline supply mainly from Russia and Turkmenistan, and on the international LNG market in which China will compete for supply notably with Japan. Recent research has, however, highlighted the methane gas released in shale gas developments in the US and questioned the climate change benefits of shale gas as compared to coal [61].

COAL DEMAND

8.18 Coal is currently the lowest cost and most accessible form of energy in China, and makes up 71% of China's primary energy supply and four-fifths of electricity generation [8]. China is also, by far, the largest coal producer in the world, with output of more than 2 billion tonnes in 2008, more than double US production [7].

8.19 In the IIASA Baseline scenario, coal continues to dominate primary energy demand, with demand approximately doubling between 2010 and 2050. This is compared with a peaking of coal demand between 2020 and 2030, as shown in Table 8.4, in both the IIASA Mix and Efficiency scenarios. The feasibility of increasing production on the scale implied by the Baseline scenario can be questioned not only on environmental grounds but also in relation to accessible coal reserves, and their transportation to demand centres.

8.20 While China's total coal reserves are vast, at 4552 Gt of proved exploitable reserves, the only coal resources taken into account for detailed planning purposes are about 115 Gt, representing about 50 years at current production rates. Further exploration can be expected to increase these proven reserves, but future reserves will not be as accessible as those mined in the past [62].

Table 8.4: Projected coal demand in CPA region for the IIASA Baseline and abatement scenarios

IIASA scenario	**Primary coal demand, Gt / year**				
	2010	**2020**	**2030**	**2040**	**2050**
Baseline	2.90	3.81	4.48	5.32	6.58
Mix	2.90	2.79	2.21	1.73	1.64
Efficiency	2.82	2.56	2.46	2.13	1.47

8.21 Coal mining has so far been concentrated in the Provinces nearest to the centres of demand in Eastern China. However Figure 8.5 shows that by far the largest remaining forecast reserves are further to the West, for instance in Xinjiang province, some 3,000 Kilometres west of the East coast. The majority of the reserves at less than 1000 metres depth, and therefore relatively economic to mine, are also in Xinjiang Province, but a lack of transport infrastructure, scarce water resources and fragility of the ecosystem are potentially major barriers to accessing this [43].

Figure 8.5: Estimated coal reserves in China, in billions of tonnes (Gt) [62]

8.22 Some 50-60% of China's coal production is from big state owned mines equipped with state of the art technology. US mining company Peabody is a major supplier of advanced longwall equipment. However 30-40% of production is from town, village, and enterprise mines with low average rates of extraction, much less advanced equipment, and in some cases poor safety records [9]. The Chinese authorities have attempted, in the past, to close the less efficient mines but have been frustrated by the pressure of rapidly increasing coal demand.

8.23 In 2009 China imported some 100 Mt of coal and in 2010 this rose to 170 Mt [9]. This was less than 10% of China's demand but large enough, in relation to internationally traded coal to have a big impact on world markets. As well as supplies from Australia and Indonesia, China is establishing deals with Russia and is becoming increasingly involved with Mongolia which has massive coal deposits but as yet minimal infrastructure.

8.24 The rate of growth of China's coal power generation is likely to be constrained by policy considerations but also by the difficulties of modernising the less advanced part of the mining industry and the limitations of the reserves that are currently accessible to centres of demand. China will face a strategic energy policy decision of how much investment to make in infrastructure to bring coal from the far West. This could take the form of railways to transport coal or high voltage direct current lines to bring power. Other options include synthetic natural gas (SNG) and coal-to-liquid technology. China's strategy of developing giant coal-power bases, integrating mining and generation, suggests that China may adopt a coal-by-wire approach, which may provide added flexibility for opening up new regions for renewable generation. Whether new transmission is cheaper than new railways over these distances is a debatable question [9]. A recent study suggests that the optimal strategy might be for heavy investment in HVDC lines to Shaanxi Province in central China, but rail links to bring coal from Xinjiang in the far West. This is on the grounds that power generation in Xinjiang may be constrained by lack of water [63].

NUCLEAR FUEL

8.25 A rough estimate using an average consumption (in a 'once-through' cycle) of 200 tonnes of uranium (tU) per GWyr shows that a linear increase in uranium-fuelled capacity of 300 GW to 2050 would require around 1 MtU. The current estimated reserves in China are 100,000 tU [64], with global reserves of conventional uranium estimated at 5.4 MtU [1], [65]. Whilst both of these estimates may be conservative, it is clear that uranium supply will be a key strategic issue for China. Alternatively, China may choose to develop capabilities in thorium fuel cycles (as in India), in advanced fuel reprocessing or, in the longer term, in fast breeder reactors. Each of these technologies would reduce the reliance on uranium whilst increasing fuel economy, but would require significant long-term investment with uncertainty around the eventual competitiveness of the technology.

ELECTRICITY TRANSMISSION AND DISTRIBUTION

8.26 The development of China's power grid represents a critical opportunity to provide the underpinning for a low carbon energy economy of the future. Because the basic frameworks of power infrastructure tend to be long lasting, the grid investments that China makes in the coming decade will influence the structure of its energy economy in 2050.

8.27 The existing high voltage grid is currently concentrated in Eastern China with a limited linkage to Western and Southern China. China's wind power potential is concentrated along the East coast and also in Northern China (see Figure F.1 in Annex F for an estimate of the wind resource in China). Although China is the world leader in wind power by installed capacity, more than half the electricity generation goes unused because of the limitations of the grid connections [66]. China's greatest solar power potential is in the far West, and the hydropower potential is concentrated in the South West region, which is estimated to have about 500 GW of potential [67].

8.28 Because of the assumed demand side energy efficiency improvements the total of Chinese electricity demand in 2050 in the Mix and Efficiency cases is no greater than today (as shown in Figure 3.1). Nevertheless, developing the grid is central to low carbon options for China's energy supply, not only because of the need to access renewable energy from across the country, but also because low carbon solutions, especially for transport and buildings and industry, are expected to require a much greater penetration of electric power in these sectors. The larger contribution of variable renewables to the power generation mix in the Mix and Efficiency cases (Figure 3.1), as well as the increase in new forms of electricity demand such as electric vehicle charging and heat pumps, will also require an increasingly flexible or smart grid.

8.29 The Chinese government has a major programme of investment in upgrading the grid, including the integration of regional networks. For the first time, in 2008, investment in the transmission grid was greater than that in the generation sector. In 2009, the State Grid Company invested $44 billion into grid infrastructure and intended to increase this to $33 billion, in 2010 [8]. The 12th Five Year Plan includes an ambitious programme of enhancing West-East transmission and the establishment of five strategic energy bases including the Far west (Xinjiang) the North (Inner Mongolia), and Southeast China [68]. While this is mainly focused on the more efficient use of coal it also opens the door to better use of renewables. Progress in grid development over the next decade will therefore be a critical factor in determining the long term outlook for China's energy economy.

8.30 Since April 2002 (Scheme of the Reform for Power Industry) China's national grid has consisted of the State Grid Corporation of China, with five sub-grids in the north supplying about 1.1 billion people, and the China Southern Power Grid with 230 million customers. A spatial view of these regional power grids is given in Annex F, Figure F.2. China has invested a great deal in increasing the extent of its electricity transmission grid, with the high voltage network growing in length by over 50% since 2000 [1]. One of the key projects in China's power sector is to integrate these sub-grids into a national grid, through policies such as the west–east power transmission [69].

8.31 It is clear that future expansion and integration of transmission projects will require the use of alternating current (AC) networks and, over long distances, high voltage direct current (HVDC) networks. Current source converters (CSC) are likely to be used for converting AC to DC and vice versa, as voltage source converters (VSC) are presently limited to 1 GW or less. CSC up to +/- 800 kV should be able to transmit 6.4 GW of power through single overhead circuits. These CSC HVDC links are economical when the distance between two power systems is over 800 km. There are some drawbacks to CSC HVDC however such as the cost of the size and the cost of the converter stations (with extensive switchyards required for filters and shunt capacitors).

URBAN PLANNING

8.32 The urban population in China is expected to exceed 1 billion by 2030 from ca. 600 million today. This is expected to have great impact on transport infrastructure and urban form [70]. Chinese cities are distinctive in their rapid development and in exhibiting widely varying development pathways [71], as well as in their disproportionate impacts on energy consumption and associated CO_2 emissions.[22] Many countries including China have attempted to apply integrating urban and transport infrastructure planning to provide their services more efficiently, with varying degrees of success. This includes facilitating modal shifts in transport by increasing mixed-use areas; efficient district heating planning and operation; and distributed electricity generation potentially coupled with a smarter demand. Decisions made in the next 10-20 years when a significant phase of urbanisation is expected to take place could have an enduring impact on energy use in Chinese cities, largely due to the inertia and slow turnover in the transport and buildings sectors.

[22] The 35 largest Chinese cities accounted for only 18% of population but 41% of GDP and 40% of CO_2 emissions in 2006 according to Dhakal [71].

8.33 In 2010, a number of low carbon pilot provinces and cities were announced by NDRC, including the provinces of Guangdong, Liaoning, Hubei, Shaanxi and Yunnan, and the cities of Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang, and Baoding. In addition, there is a growing trend of cities joining international initiatives in this respect (e.g. Beijing and Shanghai in C40, or Shenyang in ICLEI). This is clearly a prime area for international collaboration.

9 Conclusions

9.1 There are several feasible pathways for China to reduce greenhouse gas emissions to 2050 which are broadly consistent with a global goal of limiting global warming to 2^{o} Celsius. IIASA's Baseline scenario, in which China continues to be largely reliant on unabated coal for its energy supply, and with energy efficiency improvements falling short of what could be possible even under business-as-usual assumptions, itself poses some major policy issues and challenges, in addition to the more-than-doubling of CO_2 emissions to 2050. The significant increase in coal demand can be questioned, not only on environmental grounds but also in relation to accessible coal reserves. This scenario also raises problems of high oil import dependency and higher levels of local environmental pollution, compared to the abatement scenarios.

9.2 IIASA's Mix abatement scenario demonstrates how CO_2 emissions could be reduced to less than 3 $GtCO_2$ by 2050. Coal demand is reduced to a quarter of the level in the Baseline scenario and oil demand less than half. Local environmental pollution is reduced as is oil import dependency. There are strong policy reasons for China to seek a more environmentally friendly route and, indeed, this was the message of the Chinese Government in announcing its 12th Five Year Plan. Imperial's detailed analysis of the end-use sectors shows that a level of around 3 $GtCO_2$ by 2050 is feasible using a range of currently available, close-to-commercialisation, and in some cases known but unproven (e.g. CCS) technologies.

9.3 The largest part of the potential CO_2 savings in Imperial's abatement scenario comes from decarbonising the electricity sector. There is considerable uncertainty as to which low carbon power technologies will prove the most cost effective and continuing research, especially into CCS, solar PV and advanced nuclear technologies, is important. Meanwhile it makes sense to deploy a wide range of options. China's wind, solar, and hydro resources are highly dispersed geographically and the development of a strong, smart, long distance grid will be essential to exploit them fully, as well as to balance intermittent and variable supply with new sources of demand.

9.4 Energy efficiency across the industry, transport and buildings sectors will also be critical to achieving a low carbon pathway to 2050, perhaps more so than decarbonising electricity, depending on the view that is taken of business-as-usual energy efficiency improvements. Energy efficiency, combined with decarbonised electricity, would lead to large reductions in fossil fuel demand at low or negative cost and is clearly an attractive option. However, as with other countries, the challenge is to develop the institutions and policies necessary to monitor, regulate, and incentivise these changes. International collaboration with developed countries with greater experience could be helpful in some of these areas, especially at regional and local levels. In particular, careful urban planning could have a big influence on vehicle ownership and use, a topic that deserves more analysis than we have been able to carry out for this report.

9.5 CCS plays an important part in reducing CO_2 emissions in the industry sectors. If China decides to adopt Coal to Liquids technology on a large scale, CCS will also be needed to abate CtL emissions in the energy conversion sector. The demonstration of CCS in industrial processes on a commercial scale is therefore critical.

9.6 In the transport sector, electric and hybrid vehicles make a big difference to oil demand and transport emissions towards the end of the period. The critical issues here will be the need for R&D to increase battery energy density and reduce cost, the development of charging infrastructure, and consumer preferences.

9.7 In the buildings sector, aside from energy efficiency and decarbonised electricity, the widespread deployment of low carbon heating systems such as heat pumps and district CHP will drive emissions reductions.

9.8 As with the Baseline scenario, China's abatement pathway presents a range of energy and resource considerations. Gas is projected to represent an increasing element in China's energy mix in IIASA's Mix abatement scenario, but there remain considerable challenges to securing gas supplies from abroad or accessing potentially significant unconventional gas resources, including their climate and local environmental impact. The question of whether, and to what extent, to develop the large coal reserves in China's far West is a major strategic decision for the Chinese government. This would require large scale investment in railways or electric transmission. The transmission option would give greater flexibility, for the future, to access lower carbon energy resources. And if China continues with its ambitious nuclear programme it will need to carefully consider its access to uranium supplies, or alternative technologies that would drastically reduce its uranium demand.

9.9 If China follows a carbon abatement pathway, its technology development initiatives and large market can be expected to have a major impact on the global development, including cost reduction, of key low carbon technologies, such as wind, solar PV, electric vehicles, nuclear power, and CCS. This may open up options that would not otherwise have existed for other countries. China may be a competitive source of supply and will also represent an export opportunity. China's chosen pathway will also have a major impact on the international markets for fossil fuels.

9.10 There are, however, several areas in which China could benefit from technologies and knowledge in the developed world. These include advanced nuclear manufacturing, elements of solar PV and battery technology development, urban planning for transport and buildings, and implementation of monitoring and regulation of energy efficiency standards for buildings and appliances. In addition, the increasingly apparent requirement for a long-term and stable carbon price to support several low-carbon technologies in China points towards the need for domestic carbon trading schemes, in which the international community can bring considerable experience.

9.11 China is immensely diverse in terms of geography, climate, natural resources, and levels of economic development. Any study, such as this, of the country as a whole is bound to be limited. Further work is required to understand the specific regional development and urban and spatial planning considerations to ensure that China can achieve an appropriately integrated low-carbon energy system.

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