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A hybrid modelling approach to develop scenarios for China's carbon dioxide emissions to 2050- highlights

- Combining energy supply and demand models reveals low-carbon technology choices
- China could feasibly reduce its CO_2 emissions to about 3Gt by 2050
- This requires a drastically decarbonised power sector by 2050
- Low-carbon technologies are required in transport, buildings, and industry sectors

A hybrid modelling approach to develop scenarios for China's carbon dioxide emissions to 2050

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Abstract

109 words

This paper describes a hybrid modelling approach to assessing the future development of China's energy system, for both a "hypothetical counterfactual baseline" (HCB) scenario and low carbon ("abatement") scenarios. The approach combines a technology rich integrated assessment model (MESSAGE) of China's energy supply sectors (electricity generation and other energy conversion sectors), with a set of sector-specific energy demand models for the transport, buildings and industrial sectors. The resulting projections show that by 2050 significant reductions in China's CO_2 emissions are achievable compared to the HCB emissions and its current level. Moreover the relevance of specific technologies for emission reductions in all major sectors of the Chinese economy is demonstrated.

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1 Introduction

China's 2009 CO_2 emissions were about 7.7 Gt, having more than doubled since 2000 (EIA, 2011). Two years (2003 and 2004) saw annual increases in emissions of greater than 15%, driven by a rapid expansion of heavy industrial sectors (IEA, 2010a). In the absence of specific and additional measures, these emissions are projected to continue to rise with China's continued economic development, in some scenarios representing nearly 30% of global emissions by 2050 (IEA, 2010b). This means that the future course of China's CO_2 emissions is of critical importance for climate change mitigation.

China currently has in place a target for reducing its CO_2 emissions per unit of GDP by 40-45% on 2005 levels by 2020, as pledged in the Copenhagen Accord of 2009 (National Development and Reform Commission, 2010), but at this stage it does not have a longer term emissions reduction target beyond 2020. This could well change in the next few years, following the outcome of the 17th Conference of the Parties (COP) in Durban in November/December 2011, which stated that all Parties (i.e. countries) in the UNFCCC process would work towards a "protocol, another legal instrument or an agreed outcome with legal force" to limit global warming from 2020, to be agreed no later than 2015 (UNFCCC, 2011).

A number of recent studies have been undertaken to examine China's potential pathway to a low-carbon economy by 2050, including:

- The China-specific analysis within the IEA's (2010b) *Energy Technology Perspectives 2010*;
- The Chinese Energy Research Institute *Technology Roadmap for Low Carbon Society in China (as reported in Kejun et al, 2010)*;
- Sussex University (SPRU)/Tyndall's (2009) *China's Energy Transition – Pathways to Low Carbon Development,* as reported in Wang and Watson (2009)*;*
- Lawrence Berkeley National Laboratory (LBNL)'s (2011) *China's Energy and Carbon Emissions Outlook to 2050*;
- Stockholm Environment Institute (SEI)'s (2011) *A deep carbon reduction scenario for China*, as reported in Heaps (2011);
- UNDP's (2010) *China and a Sustainable Future: Towards a Low Carbon Economy and Society.*

This study adds to the literature by combining the least-cost optimisation model of the energy supply side from IIASA's MESSAGE model (as outlined in section 2) with detailed models of each major energy demand sector (industry, transport, buildings) to show the full range of technologies that could be deployed as part of a low-carbon pathway. The approach explicitly links energy demand levels to underlying socio-economic drivers, which allows the use of sensitivity analysis to highlight the dependence of future emissions on variables such as electricity carbon intensity, vehicle population, building floor space and heavy industry output.

Table 1 summarises some of the important features of the low-carbon scenarios from these studies. They share broadly similar economic and demographic projections, but cut across a broad range of achievable CO_2 emissions levels in 2050. The IIASA scenarios used in this study are within this range.

Study	**IEA**	**ERI**	**SPRU/Tyndall**	**LBNL**	**SEI**	**UNDP**	**IIASA**
Abatement Scenario name	BLUE Map	Low growth, low carbon	Range (S1-S4)	Accelerated Improvement	Deep Carbon Reduction	Emissions Abatement	GEA Mix and Efficiency
Global GHG concentration limit	450ppm CO_2e	not specified	550ppm CO_2e	not specified	350ppm CO_2	not specified	450ppm CO_2e
Global warming limit, ^{o}C*	2		2.9		2		2
China 2050 emissions, $GtCO_2$	4.3	5.1	1.5-4.5^	7.4	1.9	5.5	2.2-4.5^
China 2050 emissions, tCO_2/capita	3.0	3.5	1.1-3.2	5.2	1.4	3.7	1.5-3.2
China CO_2 emissions peak year	2020	Between 2020 and 2030	2020-30^	2027	2017	2027	2020-30^
GDP average annual growth (2005-2050)	5.0%~	5.7%	4.8-5.9%	5.7%~	5.1%	5.5%	5.3%
Population (2050), billion	1.43	1.46	1.40	1.41	1.41	1.41	1.42
Urbanisation (2050), % of population	78%$^{+}$	79%	not specified	79%	79%	70%	70%

Table 1: Selected studies on China's low-carbon transition pathway to 2050

Notes: * at least a 50% likelihood of limiting warming to this level as specified by the study; ^ depends on scenario; $^{\sim}$ IEA data for 2007-2050, LBNL for 2010-2050. Figure for 2005-2050 calculated using outturn 2005-2010 growth rates; $^{+}$ IEA only gives urban household share which is shown here.

Despite the impressive rise of economic output in China over the past three decades of economic growth, there remains considerable uncertainty about the future development pathway of this dynamic world region, and the degree to which such growth rates can be sustained. Additionally to unprecedented demographic dynamics and a rapidly aging population, the comparative advantage of low cost manufacturing is diminishing. This is partly a result of the economic development success and increasing wages, but also due to growing regulations including social and environmental standards. While at present the energy consumption of China is by far dominated by the industrial sector, a general shift in energy demand towards the domestic/commercial and transport sector may be expected (see for example ERI 2009). The sensitivity analysis presented in Section 3 attempts to set out the consequences (in terms of CO_2 emissions, of some of these uncertainties and dynamics going forward).

This paper is set out as follows: Section 2 outlines the methodology behind the modelling approach; Section 3 presents the most important results and sensitivities; Section 4 discusses the implications of this analysis for the research, investments and collaborations required in low-carbon activities, and concludes by highlighting further research directions.

2 Methodology

The study applies IIASA’s model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE). This is a systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Messner and Strubegger, 1999). The model provides a framework for representing an energy system with all its interdependencies from region-specific resource endowments and potentials to extraction rates, endogenous energy price generation, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space heating and cooling, industrial production processes, and transportation. In addition to the energy system, the model also includes generic representations of land-use (agriculture and forestry), which allows incorporation of emissions and mitigation options including bio-fuels, while considering the full basket of greenhouse gases and other radiatively active substances.

The MESSAGE low-carbon scenarios used for this study assign emissions reductions to the regions of the world where they could be achieved at least cost. A real world implementation of these scenarios would, of course, also depend on burden sharing of emissions targets and 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 Clean Development Mechanism, for example).

The global version of the MESSAGE model is not currently resolved at the national level. Instead it models a “Central and Planned Asia” (CPA) region, of which China makes up about 90% of both GDP and population across the period 2010-2050 (the rest of the Central and Planned Asia region is made up of Cambodia, North Korea, Vietnam, Mongolia and Laos). This study analyses three emissions scenarios for the CPA region:

- a “hypothetical counterfactual baseline” (HCB) scenario with no GHG emissions limit and assuming no additional policy beyond the existing air pollution control;
- an “Efficiency” emissions abatement scenario which emphasises investments in energy efficiency improvements and reductions of growth in energy demand, resulting in a developing country energy intensity reduction of over 3% per year compared to historically observed 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 while still remaining in a safe cumulative atmospheric emission budget over the whole 21st century;
- a “Mix” emissions abatement scenario with less aggressive demand side and energy efficiency improvements, but enhanced innovation in energy supply technologies resulting in a more diverse mix of low-carbon energy supply technologies. These also enable the achievement of more aggressive emissions reduction targets by 2050 compared to the Efficiency scenario. The Mix scenario allows emissions to peak later and at a slightly higher level than the Efficiency scenario.

These scenarios have been constructed as part of IIASA's Global Energy Assessment (GEA) study (IIASA, 2012) to describe alternative energy system transformations (pathways) towards a more sustainable future. These sustainable futures are defined by normative objectives related to reducing environmental (climate and air pollution) impacts of energy conversion and use, and coincidental attainment of development targets in the areas of energy security, and energy access. All GEA pathways fulfil these objectives. For example, the pathways all stabilize future global mean temperature increase at no more than 2 degrees Celsius above preindustrial levels, and they all lead to universal access to modern energy services throughout the world by 2030. At present in contrast 2.7 billion people globally still depend on solid cooking fuels and more than 1.3 billion are excluded from access to electricity (Foell et al, 2011).

In contrast to for example the IPCC SRES scenarios (Nakic´enovic´ et al, 2000) which were designed to reflect interactions between the drivers of energy demand and associated sensitivities, the GEA pathways all share the same assumptions about drivers, such as a common median demographic projection whereby the global population increases from almost 7 billion in 2005 to about 9 billion by the 2050s before declining toward the end of the century. The GEA pathways also share a median economic development path so as to allow for significant development in the 50 or so of the poorest countries in the world while at the same time reflecting increased resource productivity and demand growth in the richest countries dampened by changing consumption patterns and lifestyles. Projected future urbanisation rates are the only macroeconomic factors that vary between scenarios, with the Efficiency scenario reaching 64% and the Mix scenario reaching 68% urbanization at the global level in 2050. One of the salient reasons for this scenario design is the objective of GEA scenarios, to draw attention to the link between energy and internationally agreed development goals, rather than to focus on the sensitivity of energy use to variations in demographic or economic changes.

The energy demand scenarios for the GEA have been developed in close collaboration with analysts running sector-specific models in order to establish how energy demand levels, as well as the mix of energy carriers demanded, by each major energy end-use sector (transport, buildings, industry) may change from an HCB scenario to the low-carbon scenarios. The Grantham Institute at Imperial College has undertaken an independent assessment of the sector-specific demand drivers in both the HCB and low-carbon scenarios specifically for the China region, in order to more explicitly relate energy demand and energy carrier changes to socio-economic patterns and the deployment of specific low-carbon technologies. This provides an independent comparison to the energy demand inputs into the MESSAGE model. It also allows a sensitivity analysis to be undertaken, by varying some of the most important socio-economic and technology parameters, as discussed in Section 3. The underlying methodologies used in the Grantham Institute models to construct these “bottom-up” assessments of energy demand in each end-use sector are described in the three following three subsections.

2.1 Industry

The detailed Grantham Institute industry model assesses the abatement potential across the secondary industry sectors (iron & steel; chemical and petrochemical; non-ferrous metals; non-metallic minerals; machinery and transport; food and tobacco; pulp, paper and print; construction, textiles and other manufacturing). The industry sector as modelled here does not include the primary, extractive sectors such as agriculture and mining, nor the service sectors. These sectors are dealt with elsewhere – agriculture through the land use projections of the MESSAGE model, mining through the energy conversion projections of the MESSAGE model, and service sectors through the buildings emissions projections discussed in section 2.3. The industry model determines both the overall annual energy requirements for the industry sector, split by fuel type (electricity, gas, oil, coal, biomass, solar and other energy carriers) and the total annual CO_2 emissions of industry from both processes and fuel combustion.

For each industry sub-sector the future output is projected to 2050, as presented in Annex A. The projections reference existing sources (principally Kejun et al, 2010). The energy intensity of production is projected according to assumptions around the mix of production processes used in the future, and energy efficiency improvements. The fuel mix used in each sub-sector is also projected, in many cases by comparison with the current fuel mix used in countries such as Korea, Japan and the US, which at this stage have on average more advanced industrial processes. Emissions savings from Carbon Capture and Storage (CCS) are assumed to be achieved only in the iron & steel and cement sectors, which are the major producers of direct CO_2 emissions. This may be a conservative assumption however, given the potential application of CCS in the chemicals and other industrial sectors. The major assumptions around process and fuel mix changes as well as energy efficiency improvements are presented in Annex B.

Significant changes that are assumed in the Chinese industry sector to 2050 (focusing on iron and steel, chemicals and cement, which form the majority of industrial emissions) include:

- Increased share of electric arc furnace steel production, such that by 2050 a third of all iron and steel production occurs through this process. This relies on the broad availability of scrap or recycled steel, which is more likely to become available as an economy matures and existing infrastructure is replaced;
- Phasing out of less efficient kilns in cement production, the replacement of coal by biomass in kiln-firing, as well as lower clinker-to-cement ratios;
- Very widespread deployment of CCS in iron and steel and cement plants by 2050 (three-quarters of emissions captured);
- Drastically increased electrification of heating in the chemical and petrochemical sector, replacing coal usage, and significant (about 30%) improvement of energy efficiency of production through energy conservation processes.

Estimates of future fuel shares and energy intensity are particularly difficult for the chemical industry and for the less energy-intensive industries such as the manufacturing of machinery and end-user products, given the wide range of products which are often aggregated into these much broader categories. Moreover, the definition of sectors in industry differs from country to country. This makes it difficult to estimate future consumption in China by comparing its 2050 economy to other countries.

2.2 Transport

The detailed Grantham Institute transport sector model assesses all the major transport modes including road, air (distinguishing domestic and international flights), rail, and water. The model assesses both passenger transport and freight transport. The non-road transport sectors have been modelled with close reference to Heaps (2011) using the long-range Energy Alternatives Planning (LEAP) model, with major assumptions on transport activity levels and abatement shown in Annex A and Annex C respectively.

For non-road transport, the major emissions savings result from the following assumptions:

- Rail and marine travel can achieve energy efficiency improvements resulting in a reduction of energy per passenger-km of the order one-third by 2050 compared to current levels;
- Air travel achieves a one-fifth improvement in energy efficiency by 2050 compared to current levels;
- Rail (both passenger and freight) travel becomes fully electrified by 2050;

- Biofuels penetration increases to one-third of all fuel used (by energy rather than volume) in marine travel by 2050, and one fifth of all fuel used in air travel by 2050;
- Half of the domestic air travel projected by 2050 can be replaced by high-speed rail.

The model for the road transport sector is based on the model reported in Ou et al (2010). This model has considerable detail of road vehicle types, with vehicles divided into 9 categories including: heavy duty trucks (HDTs), medium duty trucks (MDTs), light duty trucks (LDTs), mini-trucks (MTs), heavy duty buses (HDBs), light duty buses (LDBs), cars, minivans (MVs), and motorcycles (MCs). The sales for these vehicles are projected with consideration of the penetration rates of mild hybrids, full hybrids, plug-in hybrid electric vehicles and pure electric vehicles. The vehicle stock in each year can be obtained from the sales projection and the survival rates for different types of vehicles.

There is a large range of projections on the future vehicle population in China by 2050. Ou et al (2010), on which this work is based, estimate about 500 million road vehicles by 2050. The central scenarios used here, however, are closer to 300 million vehicles by 2050, following more “Japanese” patterns of growth towards high urbanization levels with mixed use zoning and high capacity public transport infrastructure (Kobayashi, 2011). Activity levels of the road transport sector are shown in Annex A and major abatement assumptions are shown in Annex C, with major assumptions as follows:

- The fuel efficiency of new gasoline and diesel cars/minivans increases by about 1.4% per year to 2030, then levels to 2050, and of heavier vehicles by 0.3% per year to 2030, before levelling off to 2050;
- Fully Electric car sales achieve a steady increase to a 40% share of new sales by 2050, whilst conventional cars sold are all hybrids by 2050;
- Biofuels usage increases until by 2050 about 1/3rd of fuel (by energy) used in conventional engines is from biofuels.

This model does not consider hydrogen fuel cell vehicles specifically (as hydrogen demand in the IIASA transport abatement scenarios is also not considered), but the combined sales of hydrogen fuel cell and electric vehicles by 2050 in IEA (2010b) is about 40%, which compares reasonably closely with the assumption here of 40% sales of electric vehicles by 2050.

2.3 Buildings

The Grantham Institute buildings model assesses the abatement potential in the main energy end-use categories in both residential and commercial buildings (water heating, space heating, cooking, lighting, cooling and appliances). The model first projects the number of households and commercial buildings in urban and rural areas based on saturation curves that correlate, respectively, household habitation and commercial office space with income levels and service sector GDP, with the major projections shown in Annex A. The structure is also split into northern, transition and southern zones to account for the different climatic conditions and heating requirements. This population split is based on the UN population model, and an extrapolation of LBNL (2009). The heating requirement for each zone is derived from useful energy estimates in industrialised countries with similar heating degree days and GDP per capita.

The model projects the appliance and cooling usage in buildings, based on household income/ownership saturation curves. Where ownership data is lacking, Japanese ownership levels at similar levels of GDP/capita are used as a template model for urban areas, while rural areas take after present-day urban China. The assumptions for each major energy usage function in the buildings sector are described in detail in Annex D, but the major drivers of carbon reductions in the building sector are as follows:

- Buildings energy efficiency increases significantly compared to today’s levels, with energy used for heating per unit floor area about 60% of today’s levels by 2050 in urban areas (which account for 70% of housing by 2050) and for all commercial buildings;
- Coal-based heating is phased out by 2050, replaced by low-carbon sources such as biomass, CHP, heat pumps (using largely decarbonised electricity), solar thermal and natural gas;
- The energy intensity of lighting, cooking equipment and most appliances is about half of today’s levels by 2050 (with the exception of refrigerators where a 25% gain in efficiency is achieved by 2050).

There is considerable uncertainty around the future of the buildings sector in China given the rate of construction. Nevertheless, many of the buildings constructed in recent times have relatively short lifetimes (in many cases 30 years or less) and there is rapid urbanisation, providing opportunities for achieving a high building standard by 2050 provided the incentive, regulatory and monitoring framework is fit for purpose.

3 Results

3.1 Electricity generation and demand

Electricity generation in China grew rapidly in the most recent years. 1.7 EJ were generated in 1990 and the corresponding numbers were 3.6 EJ and 7.2 EJ in 2000 and 2005 respectively (IEA, 2007). While at present industry dominates electricity consumption, there has been remarkable success in combating energy poverty in rural areas and achieving almost universal electricity access (IEA, 2007).

Electricity demand is set to continue its growth over the coming decades as Chinese incomes rise. Figure 1 shows the total electricity generation, split by generation technology, in the three IIASA scenarios by 2050, and how this compares to 2005 electricity demand. There is a significant increase in electricity demand in the period to 2050 – by a factor of three or more.

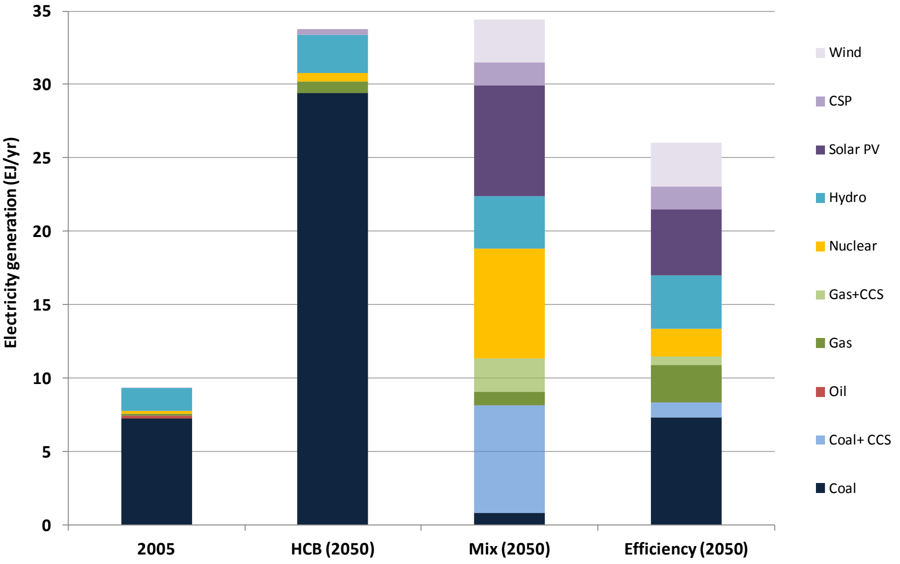

Figure 1: Electricity generation in 2005 and in 2050 in the IIASA HCB and abatement scenarios

Total generation in the IIASA Mix abatement scenario in 2050 is not very different from the IIASA HCB scenario, 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. The Efficiency scenario has about 20% less electricity demand than the HCB and Mix scenarios, as a result of greater energy efficiency measures, which more than offset the increased electrification.

Whilst the IIASA MESSAGE model accounts for the lower load factors in variable renewable generation technologies, 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 is unclear. Specific spatial and temporal modelling of demand and supply in electricity networks would be beneficial in understanding the potential for this further, not just in China but in all regions that could see increased renewable penetrations. For example, a recent study by the European Climate Foundation (ECF, 2011) on the European power system suggests that, by 2030 when the penetration of variable generation sources will have increased significantly, achieving a 10% shift in electricity demand from peak times to non-peak times through smart technologies could reduce grid capacity by 10% and back-up capacity by 35%, saving significant investment costs and reducing the volatility of power prices.

The contribution of solar PV in the IIASA MIX abatement scenario is much larger than in other studies, reflecting IIASA's relatively optimistic estimates about its future cost – solar PV generation could reach of the order $200/kWyr by 2030 and then fall further to about $100/kWyr by 2050 (using a 5% discount rate). By comparison, McKinsey (2009) projects solar PV costs of the order $500/kWyr by 2030 (using a 4% discount rate). There could be barriers to the continued cost reductions of solar PV such as limitations to the savings that could be gained from the physical infrastructure (wiring, switches, support racks and - in the case of off-grid systems – batteries) to which solar PV modules are connected, which could mean that alternative low-carbon technologies such as 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.

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 (EIA, 2010). As concerns nuclear, there remain considerable uncertainties in the wake of the March 2011 Fukushima incident around the future speed and level of deployment of the technology in China, but statements following the incident (as reported in Asia Power, 2011) have indicated that plans to 2020 and beyond may not be very greatly affected. This aside, a number of studies have projected a considerable deployment of nuclear by 2050. For example The IEA's (2010b) BLUE Map low-carbon scenario sees 318 GW of nuclear deployed by 2050, whilst Kejun et al's (2009) Low Carbon scenarios have a range of 337 - 388 GW by 2050. This compares to actual nuclear deployment of about 11 GW in 2010 (World Nuclear Association, 2011).

Figure 2 shows the resulting CO_2 intensity of electricity generation in the three IIASA scenarios, and highlights the significant decarbonisation by 2050 which would result from the Mix abatement scenario.

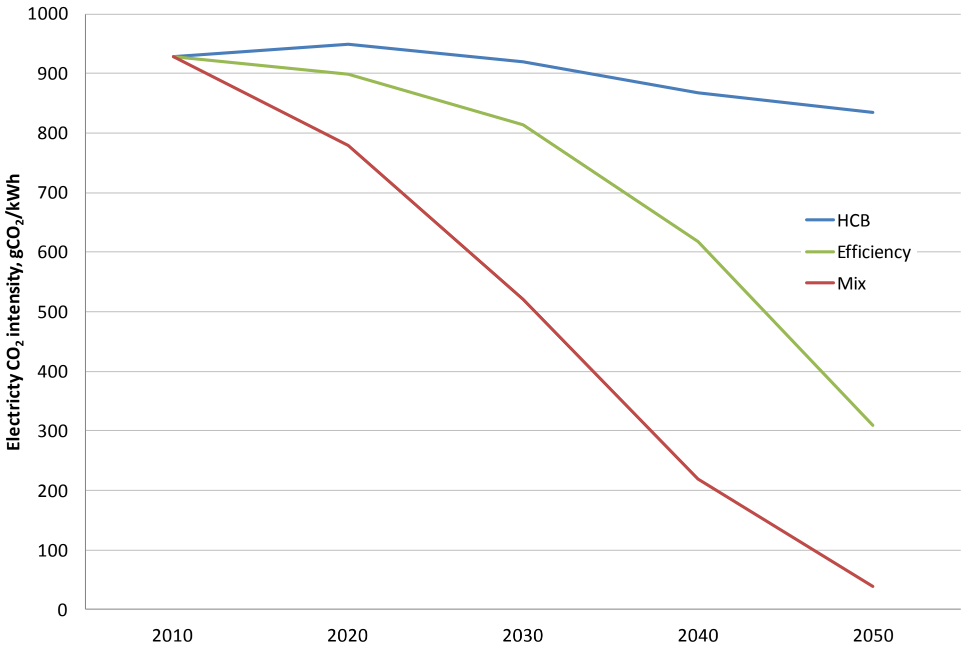

Figure 2: Electricity CO_2 intensity in the IIASA HCB and abatement scenarios

This study constructs a new HCB and Abatement scenario, hereafter labelled the “Grantham Institute HCB” and “Grantham Institute Abatement” scenarios. The former takes the IIASA HCB electricity generation CO_2 intensity, and the latter the IIASA Mix electricity generation CO_2 intensity. These electricity generation CO_2 intensities are combined with the Grantham Institute analysis (for both HCB and Abatement cases) for the industry, transport and buildings sectors to form the full Grantham Institute scenarios.

3.2 Final energy demand and emissions

Figure 3 shows the energy demand (by fuel type) in 2050 in the Grantham Institute HCB and Abatement scenarios, as compared to the IIASA HCB scenario and the IIASA Mix abatement scenario (which for the purpose of this analysis is treated as the central IIASA abatement case). The figure also shows that, compared to 2005, China will see a near-doubling of energy demand.

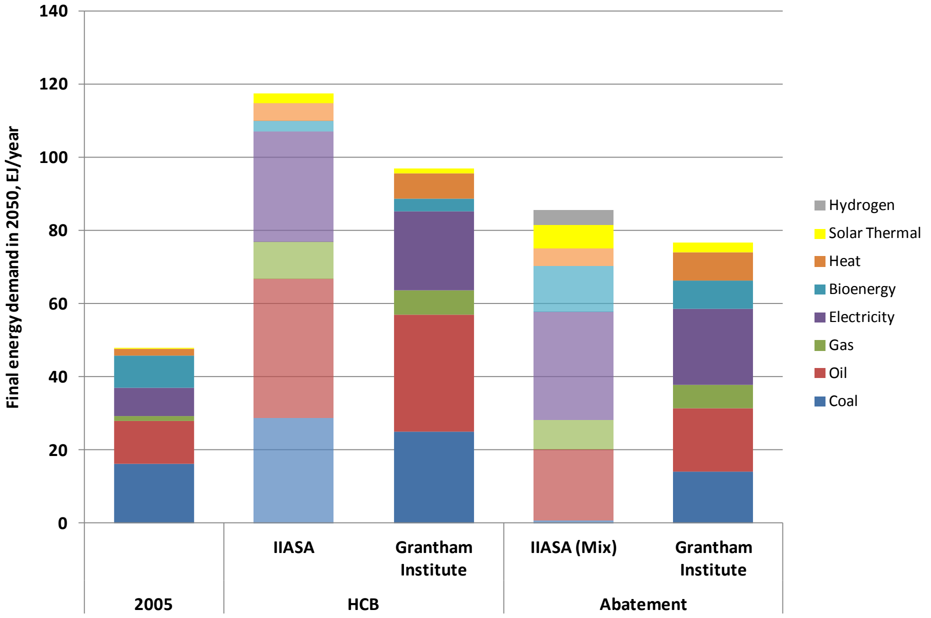

Figure 3: Final energy demand in 2050 in the Grantham Institute and IIASA HCB and Abatement scenarios

In general the energy demand projected for 2050 by the Grantham Institute scenarios is lower than that in the IIASA scenarios, for the both the HCB (17% lower) and abatement (11% lower) scenarios. For the HCB scenarios this partly reflects the greater energy efficiency improvements assumed in the Grantham Institute's projections, whilst for both the HCB and the Abatement scenarios the Grantham Institute projections are lower as they are for China alone rather than the (approximately 10% larger in GDP and population terms) CPA region. Hence the Grantham Institute bottom-up modelling provides a useful plausibility-check for the levels of end-use final energy demand which have been used in the IIASA modelling, which in total seem reasonable.

It is worth noting that the composition of final energy demand is rather different in the two abatement scenarios shown in Figure 3 - there is far more coal in the Grantham Institute Abatement scenario relative to the IIASA Mix scenario, and about 10 EJ/year less electricity demand. Coal demand is higher principally because IIASA assumes a range of substitutes (including biomass) for coal used as a feedstock in the industry sector, whereas the Grantham Institute'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. The IIASA Mix scenario also assumes a large share of coal to be converted to liquid or grid based carriers by 2050. 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 the Grantham Institute's modelling. This could be the result of less aggressive assumptions by IIASA on the energy efficiency improvements of this electrical equipment, where the Grantham Institute's research indicates significant potential.

As shown in Figure 4, the higher coal demand in the industry sector in the Grantham Institute 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 abatement scenario has a slightly lower oil demand than the Grantham Institute Abatement scenario, but the total savings are principally lower due to the fact that the emissions in the Grantham Institute HCB scenario are lower than in the IIASA HCB scenario. In the buildings sector 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 Grantham Institute Abatement scenario mean that the Grantham Institute Abatement scenario shows smaller emission savings compared to the IIASA Mix scenario.

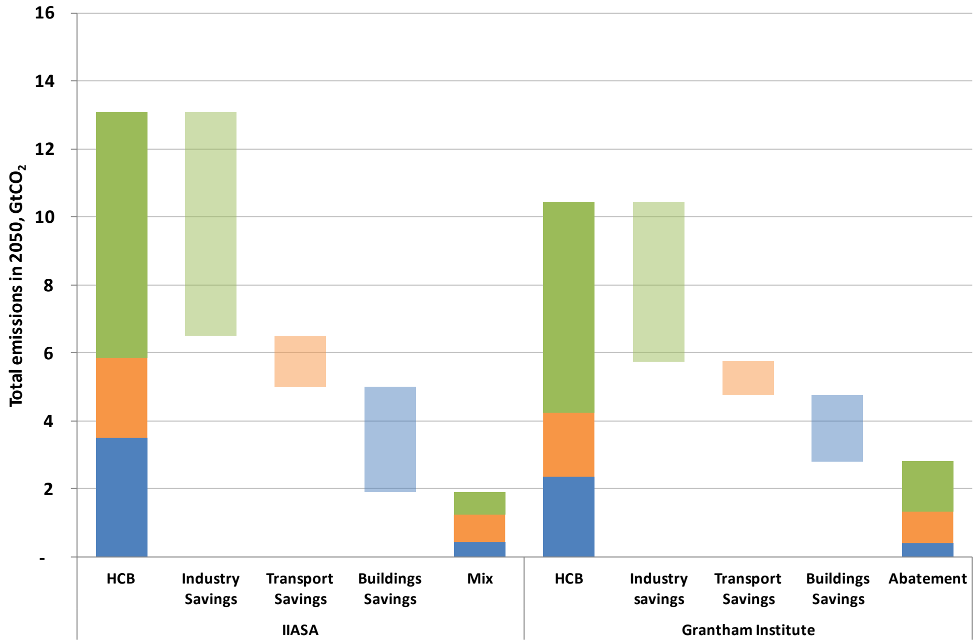

Figure 4: Emissions savings in Grantham Institute and IIASA abatement scenarios by 2050

Notes: Emissions do not include energy conversion emissions, which are 2.8 $GtCO_2$ in the IIASA HCB and 0.4 $GtCO_2$ in the IIASA Mix scenario by 2050. Grantham Institute analysis does not consider the energy conversion sector. For comparison purposes, China's energy and industry CO_2 emissions in 2009 were 7.7 Gt (IEA, 2010a)[1].

Nevertheless, the IIASA and Grantham Institute scenarios report a broadly similar message – that the greatest abatement opportunities come from the industry sector (principally through electrification and decarbonisation of the electricity sector) and that emissions from these end-use sectors (which includes electricity emissions) could be reduced to below 3 $GtCO_2$ in China by 2050.

It should be noted that the emissions shown in Figure 4 do not include emissions from the energy conversion sector, which in the IIASA HCB scenario are 2.8 $GtCO_2$, and in the IIASA Mix scenario are about 0.4 $GtCO_2$, by 2050, principally due to the application of CCS technologies in energy conversion (for example Coal-to-Liquids) processes.

3.3 Sector-level emissions reductions

The sector-level modelling, which relates fuel demand and hence emissions to the penetration of specific low-carbon technologies, allows an analysis of the emissions savings from each major low-carbon technology and measure. Figure 5a shows the results for the industry sector.

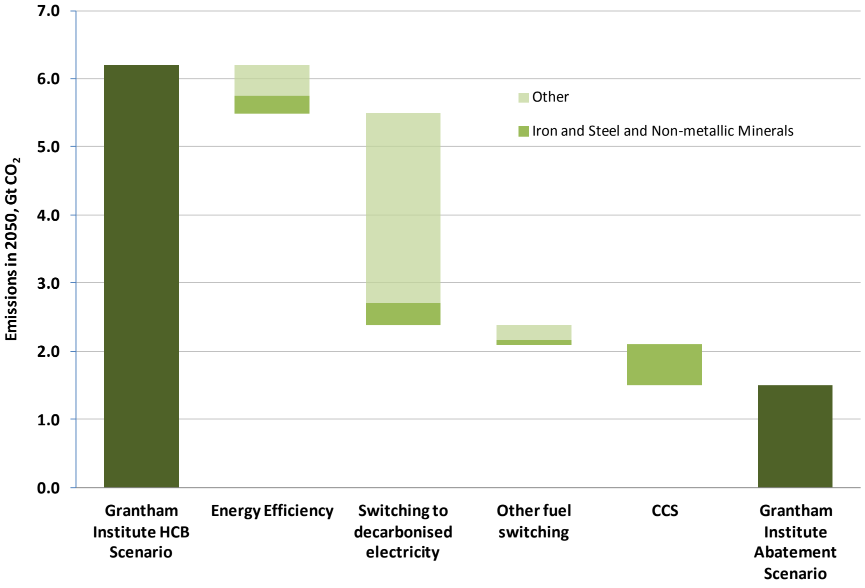

Figure 5a: Breakdown of 2050 emissions savings in the Industry sector in China

The largest element of emissions savings is linked to the decarbonisation of electricity. Energy efficiency, through the adoption of best available technologies in industrial plants, and CCS in iron & steel and cement, could also make sizeable contributions to overall industrial emissions savings.

Figure 5b shows the results for the transport sector. About two fifths of the savings come from electric vehicles, with the remainder from biofuels and vehicle efficiency. Most of the remaining savings in the transport sector would come from efficiency improvements in rail, water and air transport, and the electrification of railways.

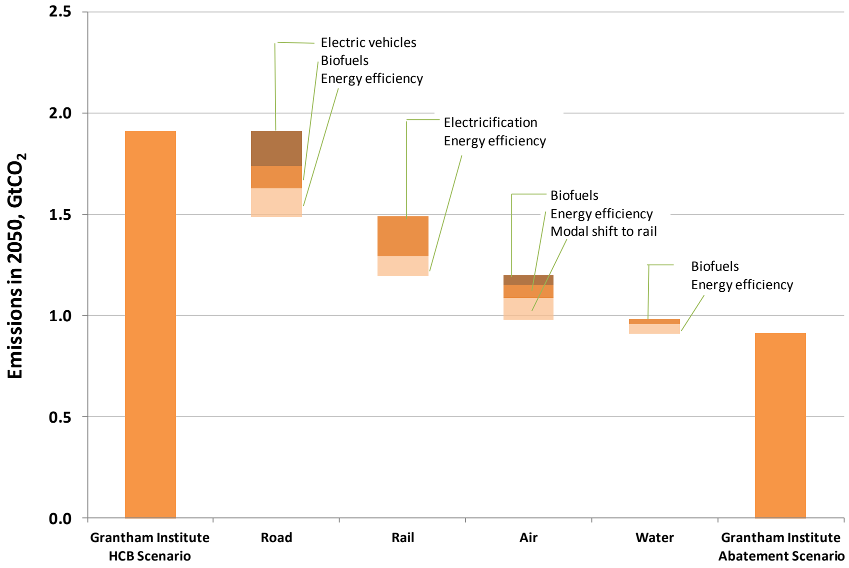

Figure 5b: Breakdown of 2050 emissions savings in the Transport sector in China

Figure 5c shows the results for the buildings sector. The emissions savings identified will depend on the widespread deployment of low carbon heating technologies such as heat pumps, the availability of low carbon electricity, and efficient building standards. Annex E details the savings indentified by each major measure in each sector.

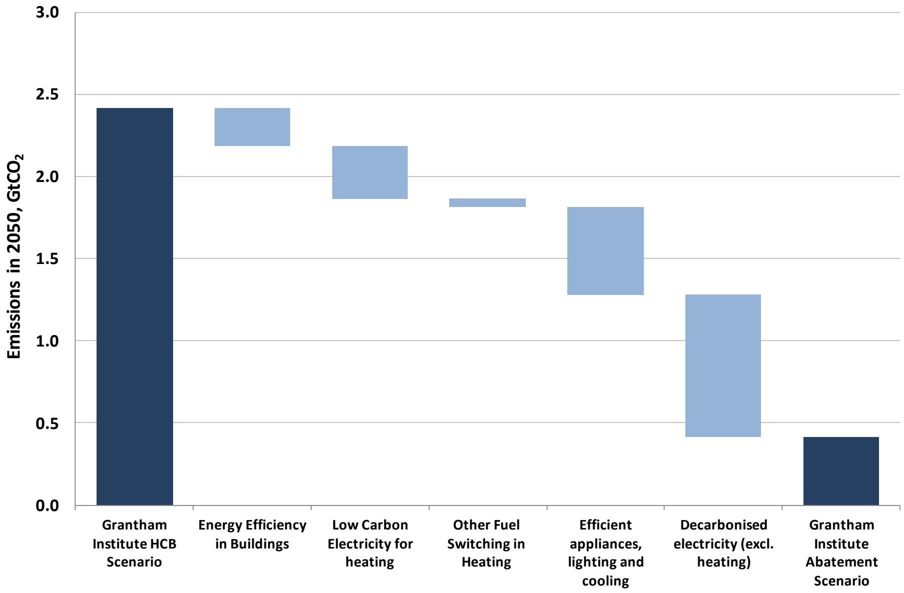

Figure 5c: Breakdown of 2050 emissions savings in the Buildings sector in China

3.4 Costs of low-carbon scenarios

Consumption losses in China in the IIASA Mix scenario are about 2% of GDP in 2050, relative to the HCB scenario. This would need to be compared against a projected growth in consumption of about 500% in the CPA region over the period to 2050. This figure is derived from the MESSAGE modelling alone, whose focus is more on the energy supply technologies (i.e. electricity generation and other energy conversion). The modelling accounts for the economic benefits of reducing energy usage as a result of the uptake of energy efficiency technologies, but it does not take full account of the costs of investments in and operation of low-carbon demand-side technologies such as low-carbon electric vehicles, for example. As such, it could be an underestimate of the total cost to the Chinese economy. On the other hand, this cost does not state the share of costs met within China and the share met through foreign finance, through mechanisms such as the Clean Development Mechanism, for example.

3.5 Sensitivity analysis

The development of three relatively simple but transparent energy end-use sector models as described in Section 2 allows a straightforward assessment of the sensitivity of emissions projections to a range of factors, thereby allowing the consideration of a range of uncertainties when projecting to 2050.

For example, in the industry sector, the degree to which China will have transitioned away from heavy, energy-intensive industry is unclear. In addition, the deployment of carbon capture and storage is required for a significant share of emissions reductions by 2050. This technology has not yet been commercially proven in industrial applications, so there remains a possibility that it may not be viable, particularly in the absence of global carbon markets and other mechanisms to support its wide-scale deployment. Finally, the Grantham Institute Abatement scenario uses IIASA's Mix abatement scenario's electricity CO_2 intensity value, where electricity becomes highly decarbonised (below 50 gCO_2/kWh) by 2050.

Figure 6a illustrates how industrial emissions (including indirect emissions from electricity generation) would change if these assumptions were changed. Assuming heavy industrial production increased by 25% by 2050, overall industry emissions would increase by about 0.1 $GtCO_2$ by 2050. Without CCS, industrial emissions would increase by about 0.6 $GtCO_2$ by 2050. Using the IIASA Efficiency abatement scenario's electricity CO_2 intensity (280 g/kWh by 2050), overall industry emissions would increase by about 0.9 $GtCO_2$ by 2050.

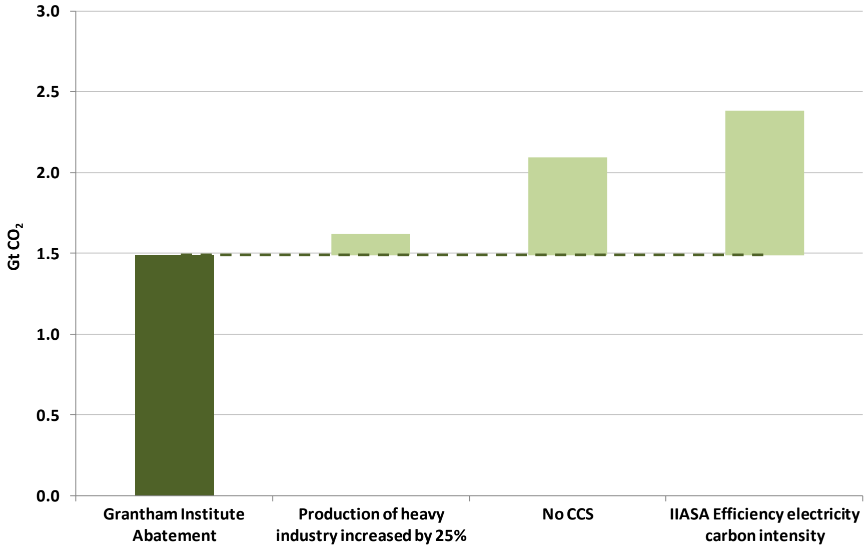

Figure 6a: Sensitivities for 2050 industry CO_2 emissions in Grantham Institute Abatement scenario

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, the electricity CO_2 intensity, and the road vehicle stock by 2050. Figure 6b 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 (excluding motorcycles) by 2050 (in line with the assumption by Ou et al, 2010), rather than about 300 million, as assumed in the Grantham Institute model. This higher vehicle stock would result in an additional 0.3 $GtCO_2$ emissions by 2050. Also the lifecycle GHG intensity of biofuels is highly variable and subject of debate if their use were massively expanded (for a fuller discussion see Melillo et al, 2009).

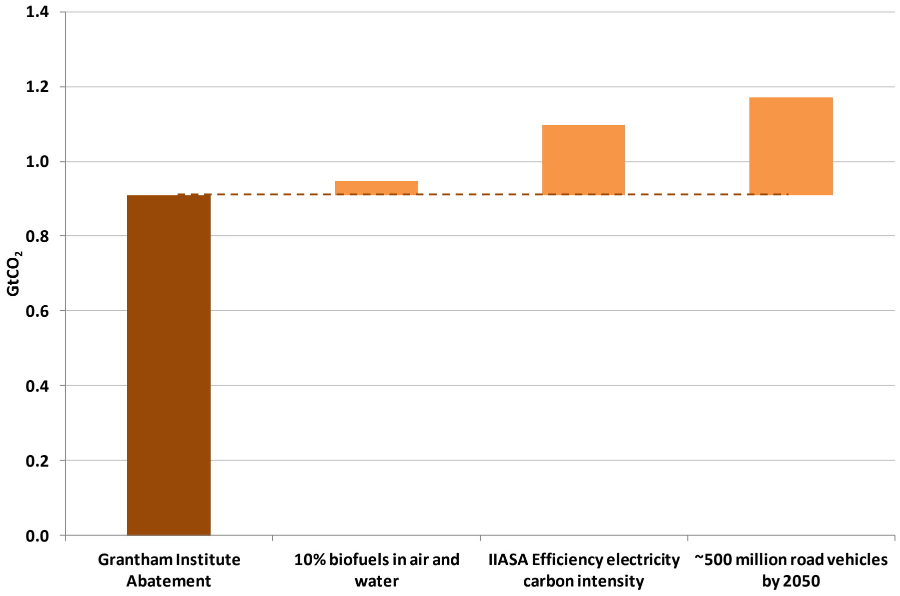

Figure 6b: Sensitivities for 2050 transport CO_2 emissions in Grantham Institute Abatement scenario

In the buildings sector, figure 6c 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 abatement scenario's electricity CO_2 intensity almost doubles overall buildings emissions, as there is significant electrification of all buildings energy services by 2050.

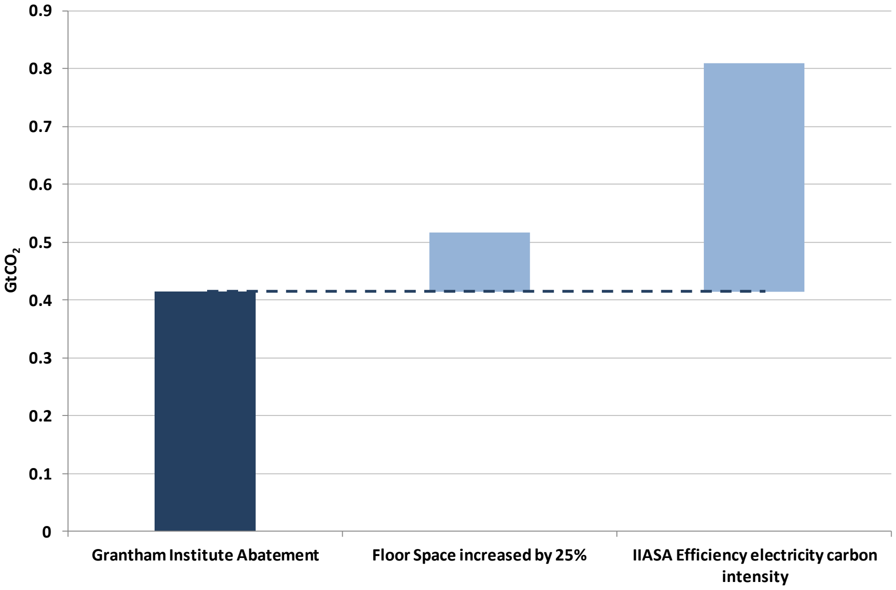

Figure 6c: Sensitivities for 2050 buildings CO_2 emissions in Grantham Institute Abatement scenario

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 Grantham Institute Abatement scenario, underlining the importance of achieving a highly decarbonised electricity generation system by 2050.

4 Discussion and Conclusions

Combining an energy-technology model such as MESSAGE, which least-cost optimises energy supply for given energy demands, with a more detailed analysis of energy technology options in the main energy demand sectors (industry, transport, buildings) provides an overview of the economy-wide range of technology options which could be efficiently deployed when aiming for fast and deep CO_2 emission reductions.

For China the analysis suggests that there are emissions-reduction pathways which could significantly reduce China's CO_2 emissions by 2050, to an order of 3 $GtCO_2$, less than a fifth of the level that might be reached in a hypothetical counterfactual baseline (HCB) scenario by 2050 and much lower than the approximately 8 $GtCO_2$ emitted in 2009, despite a 500% increase in GDP between 2010 and 2050. The technologies which emerge from the least-cost supply-side modelling, and from demand-side modelling which is based on a consideration of best-practices in other countries and realistic technology developments in the future, gives rise to a number of policy and research considerations, both for China directly and also the international community.

The largest factor in the decarbonisation of China's energy sector to 2050 is the availability of low-carbon power. There is considerable uncertainty as to the relative costs of nuclear power, fossil power with CCS, hydro, solar PV, and wind. It makes sense to develop all these sources to achieve a diverse, low-carbon generation mix. 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 and new markets for energy services will be beneficial.

Energy efficiency across the industry, transport and buildings sectors will also be critical to achieving a low carbon pathway to 2050. These measures 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 and to appropriately price the climate change externalities of its conventional (fossil) fuels. International collaboration, especially at city and provincial levels, where careful urban planning will be needed to limit uncontrolled growth of transport and heating emissions as population centres expand, could be valuable in areas where developed countries have greater experience to draw on.

The adoption of CCS appears to be central to the achievement of emissions reductions in the power and industry sectors. This underlines the need for early commercial scale development of CCS in electricity generation and, in addition, research into its applications to industry. China is already involved in a number of international collaborations on CCS, including with the UK and other European partners, but this should be an area of urgent international focus.

Whilst China has implemented targeted policy interventions such as for example direct R&D and deployment support for onshore wind, there is in addition an increasingly apparent requirement for a long-term and stable carbon price or equivalent support mechanism for several low-carbon technologies which will continue to be more expensive than their fossil-fuel based alternatives. China is now looking to develop and pilot domestic carbon trading schemes which could help do this.

A number of areas remain to be assessed in further detail to provide a comprehensive strategy for China to transform its economy to a low-carbon one. For example this analysis only examines CO_2 emissions, whereas the future growth and mitigation potential of non-CO_2 GHGs (see for example Lucas et al, 2007) will be essential when considering China's contribution to an overall global strategy to limit global warming. In addition, this analysis only considers emissions originating from within China, and does not take into account the full consequences of any shift in emissions from China to other countries should it decide to move away from energy-intensive industrial production. Finally, the analysis as presented here does not consider the wider impacts of low-carbon technologies on China, including on local air pollution, water stress and land usage. A broader analysis of these impacts is presented in Grantham Institute (2012)'s study upon which this paper is based.

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Annex A – Socio-economic and activity drivers in modelling

	2010	2020	2030	2040	2050
Socio-economic drivers					
GDP ($US2005 trillion, PPP)	3.631	7.212	11.876	16.735	22.369
Population (million)	1,354	1,431	1,462	1,455	1,417
Urbanisation (% of population)	45%	53%	60%	67%	70%
Industry output (metric tonnes)					
Iron and Steel	500	700	750	650	490
Chemical and Petrochemical	166	214	224	250	264
Non Ferrous Metals	16	19	21	24	27
Non Metallic Minerals	1240	1600	1600	1200	900
Machinery and transport	169	311	480	635	831
Food and Tobacco	993	1051	1073	1073	1066
Paper Pulp and Print and wood	78	110	115	120	120
Other (incl. construction, textile)	111	133	156	178	200
Transport activity					
Non-road passenger transport (trillion passenger km)					
Rail	0.82	1.12	1.34	1.39	1.31
Domestic air	0.18	0.32	0.50	0.74	1.07
International air	0.15	0.27	0.43	0.62	0.89
Non-road freight transport (trillion tonne km)					
Rail	2.71	3.87	4.56	4.90	5.12
Water	7.11	11.17	14.66	17.78	21.28
Road transport (millions of vehicles)					
Trucks	17.25	32.01	40.90	46.56	49.99
Buses	5.44	9.26	10.47	10.29	9.17
Cars and vans	51.52	125.49	177.52	225.20	271.33
Motorbikes	91.63	114.40	119.46	119.48	119.48
Buildings activity					
Urban households (millions)	237	347	404	426	442
Rural households (millions)	182	157	141	125	99
Commercial floor area (million m^2)	3569	7765	10745	14226	18835

Annex B – Abatement assumptions in industry model

Sector	Major assumptions in abatement scenario	Sources

Iron and steel	• Average energy intensity drops from 24 GJ/tonne in 2005 to 17.1 GJ/tonne in 2050 owing to the following improvements:
	  • Shift from smaller inefficient to larger advanced plants.
	  • Increased share of electric arc furnaces (33% by 2050)
	  • Increased share of continuous and thin slab casting
	• Electricity share increased from 12% to 17% owing to increased share of EAFs. Sector remains heavily reliant on coal and coke, although small amount of biomass penetration (5%).
	• By 2050 75% of iron and steel production would be from plants with CCS.
		IEA (2010b), Wang et al (2007), LBNL (2008),

Chemical and petrochemical	• Average energy intensity improves from 42.5 GJ/tonne in 2005 to 30.9 GJ/tonne in 2050. • China tends towards the fuel share mix observed in the Korean Chemicals sector in 2005. The shares of heat, gas and oil remain similar to today, with coal increasingly replaced with electricity (45% in 2050) and biomass (6% in 2050).	Kejun et al (2009), UNIDO (2008)
Non ferrous metals	• Energy intensity develops from 127 GJ/tonne in 2005 to 50.2 GJ/tonne in 2050 due to enhanced process efficiency. • China tends towards the fuel share mix observed in the German non-ferrous metals sector in 2005. The shares of heat and oil remain similar to today, with coal increasingly replaced with electricity (58% in 2050) and gas (21% in 2050).	LBNL (2011), UNIDO (2008)

Non metallic minerals	• Average energy intensity develops from 3.2 GJ/tonne in 2005 to 2.4 GJ/tonne in 2050 owing to the following improvements:
	  • Increased share of BAT dry kilns with pre-calciner and pre-heaters (increasing from 40% in 2005 to 80% in 2050)
	  • Phasing out of vertical shaft kilns (20% in 2050, down from 52% in 2005)
	  • Increased share of blended cements. Clinker to cement ratio decreases from 0.77 in 2005 to 0.74 in 2050.
	• Coal increasingly replaced by biomass reaching a penetration of 38% biomass by 2050.
	• Penetration with CCS assumed to be 75% of cement production by 2050.
		IEA (2010b)

Machinery and transport	• Average energy intensity develops from 15 GJ/tonne in 2005 to 11.7 GJ/tonne in 2050 due to enhanced process efficiency. • China tends towards the fuel share mix observed in the German machinery and transport sector in 2005. The shares of heat, oil and electricity remain similar to today, with coal increasingly replaced with gas (reaching 26% in 2050).	UNIDO (2008)
Food and tobacco	• No energy intensity improvement assumed over time • China tends towards the fuel mix observed in the US in 2005. Shares of electricity, heat and oil remain similar to today, with coal increasingly replaced by biomass (reaching 14% in 2050) and gas (6% in 2050).	UNIDO (2008)
Pulp, paper and print	• Average energy intensity develops from 15.4 GJ/tonne in 2005 to 9.6 GJ/tonne in 2050 due to enhanced process efficiency. • China tends towards the fuel share mix observed in the Korean pulp and paper sector in 2005. The share of heat remains similar to today. Gas, electricity and oil increase marginally and an increasing penetration of biomass (14%) resulting in coal decreasing from 54% to 24% by 2050.	LBNL (2011), UNIDO (2008)

Other (incl. construction and textile)	• No energy efficiency improvements in this sector - average energy intensity was 25 GJ/t in 2005. • No change in fuel share assumed compared to 2005 levels.	Own assumptions

Annex C – Abatement assumptions in transport model

Mode	**Major assumptions in abatement scenario**	**Sources**
Road	• The fuel efficiency of new gasoline and diesel cars/minivans increases by about 1.4% per year to 2030, then levels to 2050, and of heavier vehicles by 0.3% per year to 2030, before levelling off to 2050; • Fully Electric car sales achieve a steady increase to a 40% share of new sales by 2050, whilst conventional cars sold are all hybrids by 2050; • Biofuels usage increases until by 2050 about 1/3rd of fuel (by energy) in conventional engines is from biofuels.	Ou et al (2010)
Rail	• Freight and passenger rail energy intensity improves by 1/3rd by 2050; • Rail electrification increases until it is fully electric by 2050.	Heaps (2011)
Air	• Half the domestic air travel assumed in the HCB scenario is replaced by high speed rail by 2050; • Energy intensity of air travel improves by 1/5th by 2050; • Biofuels increase their share to 1/5th by 2050.	Heaps (2011)
Marine	• Energy intensity improves by 1/3rd by 2050; • Biofuels increase their share to 1/3rd by 2050.	Heaps (2011)

Annex D – Abatement assumptions in buildings model

Mode	Major assumptions in abatement scenario	Sources
Residential appliances	• Energy intensity (in kWh/yr) of major appliances approximately halves between now and 2050 (in many cases reaching international best available technology (BAT) standards today). Exception is refrigerators where BAT is about 25% better than in China – this is reached by 2050	LBNL (2009)[18]
Residential heating	• In urban areas the heating intensity ($MJ/m^2/yr$) decreases by 2050 to about 60% of today's levels (so that by 2050 it is 160 $MJ/m^2/yr$), as high levels of energy efficiency (similar to the UK's Association of Environmentally Conscious Building's Silver Standard) are achieved; • In rural areas the heating intensity (currently about a fifth of urban levels) increases to urban levels by 2050; • Coal-based heating is largely phased out by 2050, replaced by a mix of natural gas, solar thermal, CHP District Heating, and high efficiency (coefficient of performance 4) Heat Pumps; • Biomass usage is assumed to become sustainable and near-zero carbon by 2050.	IEA (2010b)[4]
Residential water heating, lighting and cooking	• Water heating efficiency improves as traditional biomass is phased out by modern biomass; the efficiency of district heating networks in Northern China increases to European standards; gas used in heating is halved compared to the HCB and solar thermal water heating covers 30% of final energy demand. • A higher penetration of more efficient lighting devices including LEDs increases the efficiency of lighting two-fold by 2050; • Cooking efficiency is approximately doubled as traditional biomass cooking is replaced by efficient biomass cookstoves.	IEA (2010b)[4]
Commercial buildings	• Commercial building shell energy efficiency improves by about 40% by 2050; the efficiency of energy services increases drastically reflecting the fast turnover in the sector, and the increased use of highly efficient multi-generation heating and cooling equipment in transition and southern areas; • All incandescent and fluorescent bulbs are phased out, and LEDs achieve an 80% market share by 2050; • Water heating efficiency improves by 50% compared to the HCB. Resistive electric heating in transition areas is phased out and replaced by tri-generation heat pumps and a small penetration of individual micro-Combined Heat and Power devices.	LBNL (2011)[9], IEA (2010b)[4]

Annex E – Emissions savings in the demand sectors (Grantham Institute, 2012)

		Technology	2050 abatement ($GtCO_2$)	Key challenges to scale-up to 2050 levels
Industry		Best available technology (BAT) and energy efficiency	0.71	•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	•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	•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	•Battery cost reductions, charging infrastructure, and dependence on decarbonising electricity supply
		Biofuels	0.11	•Uncertainties in cost, availability of reliable, sustainable feedstock
		Vehicle efficiency	0.14	•Rebound effect and growing preference for larger vehicles as incomes rise
	Non-road transport	Rail, water and aviation efficiency	0.20	•Uncertainties in speed of penetration of newer aeroplane and ship hull designs
		Water, aviation biofuels	0.07	•Uncertainties in cost, availability of reliable, sustainable feedstock
		Rail electrification	0.19	•Large national rail infrastructure likely to be expensive to electrify
		Non-road: modal switch from domestic air to rail	0.11	•Rail may not be competitive for very long-distance inter-city travel
Buildings		Low carbon heating	0.53	•Increased use of CHP will require integrated urban planning •Heat pump savings rely on decarbonisation of electricity.
		Lighting, cooling and appliances	1.24	•Savings rely on decarbonisation of electricity sector
		Energy efficiency in buildings	0.23	•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 $GtCO_2$ HCB emissions for these sectors)