A Deep Carbon Reduction Scenario for China

China Economics of Climate Change Initiative

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Contents

1 Introduction

This paper presents an initial technical exploration of how China's energy systems might be altered over the coming 4 decades to allow China to meet ambitious goals for development and income growth at the same time as keeping greenhouse gas (GHG) emissions within very tight budgets that provide a reasonable chance of keeping global temperature increases below 2°C.

To explore this question two scenarios have been developed. The **Baseline** scenario examines current and historical trends in China's CO_2 emissions and projects CO_2 emissions to 2050 assuming that China continues to develop very rapidly, albeit at a slowing rate compared to the last two decades. The Baseline assumes a general continuation of current policies which include some significant efforts to address sustainability and the climate challenge, but it does not foresee any fundamental shifts in energy policy. The net result is that energy sector emissions are expected to continue to grow rapidly in the baseline. Starting from a base of 4.8 GT in 2005, energy sector CO_2 emissions reach 12.4 GT in 2030 and 18.0 GT in 2050 in the Baseline scenario, an almost four-fold increase. The baseline scenario relies upon a sector by sector review of historical trends, as well as an examination of how future energy and CO_2 emissions patterns can be expected to evolve as China develops and average income levels increase. Up until 2030 the scenario closely matches trends in energy use and CO_2 emissions foreseen in the IEA's World Energy Outlook (WEO) 2008 for China [1]. For example, the WEO Reference Scenario foresees China's energy sector emissions reaching 11.7 GT in 2030. Additional analysis has been done to extrapolate energy and CO_2 emissions patterns out to 2050.

The second **Deep Carbon Reduction Scenario** (DCRS) examines the feasibility of massively reducing China's CO_2 emissions in 2050: with energy sector GHG emissions reduced to only 10% of the 2050 levels projected in the baseline scenario or about 85% of the level in 1990. Achieving such a target is made even more difficult because the DCRS attempts to meet these reductions whilst continuing to assume the same income growth rates as in the Baseline scenario.

The DCRS pathway for China is designed to stay within an overall emissions budget for energy sector emissions of about 230 GT CO_2 between 2005 and 2050. This budget was developed by Baer et al. [2] as part of the Greenhouse Development Rights (GDRs) framework. The GDRs framework suggests a *global emergency pathway* that is consistent with giving the world a realistic chance of keeping global temperature increases below 2°C. This requires that atmospheric CO_2 concentrations peak below 420 ppm and then begin to fall. Clearly, such a pathway is extremely ambitious, but even so it implies considerable risks. Its authors estimate that its probability of exceeding 2°C is roughly 14-32%, which in the language of the IPCC, is "likely", but not "very likely" to keep warming below 2°C. Indeed, a growing number of climate scientists now conclude that 350 ppm would be a more prudent goal for concentrations. [19].

The GDRs global emissions budget is allocated among countries as follows. First, Annex 1 countries (primarily OECD countries) are assigned an ambitious trajectory that ends with emissions roughly 90% below 1990 levels in 2050. For these countries, emissions stay roughly constant until around 2013 and then decline at an essentially constant rate. Non-Annex 1 (NA1) countries, including China, are allocated a budget such that all NA1 countries show the same overall percentage decrease relative to their baselines. That percentage is set at a level that makes the whole world consistent with the overall trajectory.

Given the overall momentum for growth and development in China, and the lack of availability of technologies that can be deployed immediately on a large scale, it is simply inevitable that China's emissions will continue to climb in the next decade even under the most ambitious of mitigation scenarios. This makes the requirements for reducing emissions after 2020 particularly challenging. To stay within the overall 230 GT budget, China's CO_2 emissions need to be reduced to about 10% below their 1990 values. This figure sounds challenging enough, but as will be shown in the following paper this equates to no more than 10% of what emissions are likely to be in 2050 in a baseline scenario.

It is important to note that the DCRS developed here for China is only a technical feasibility study. It examines whether China's emissions might be cut to a level that is compatible with protecting the planet whilst also giving enough "emissions space" for China to continue to develop. It is not a proposal about the level of obligation that China should take on in any international climate negotiations. The issue of what financial burdens different parties should take on for achieving these emissions reductions is an entirely separate question.

The DCRS also is also not intended to represent a least cost development path. The analysis presented here does not examine the economics costs of different mitigation options and thus it has not attempted to find an optimized pathway that balances the costs of mitigation against the costs of failing to act to avoid climate change damages.

Finally this analysis also should not be read as a proposal for specific energy policies. A range of alternative pathways could potentially yield the same or even lower total emissions as the DCRS. The DCRS is intended only as an initial *existence proof* of whether China's emissions might be reduced sufficiently *if* the will emerged to do so, both within China and in the rest of the world.

2 Methodology

The two scenarios described here have been developed using SEI's LEAP energy modeling system (Figure 1): a transparent and user-friendly accounting-based software tool for scenario-based energy analysis and GHG mitigation assessment [9, 10].

More information on LEAP is available at www.energycommunity.org. Both LEAP and the LEAP data set containing these scenarios for China are also available for download at the LEAP web site or by emailing leap@sei-us.org.

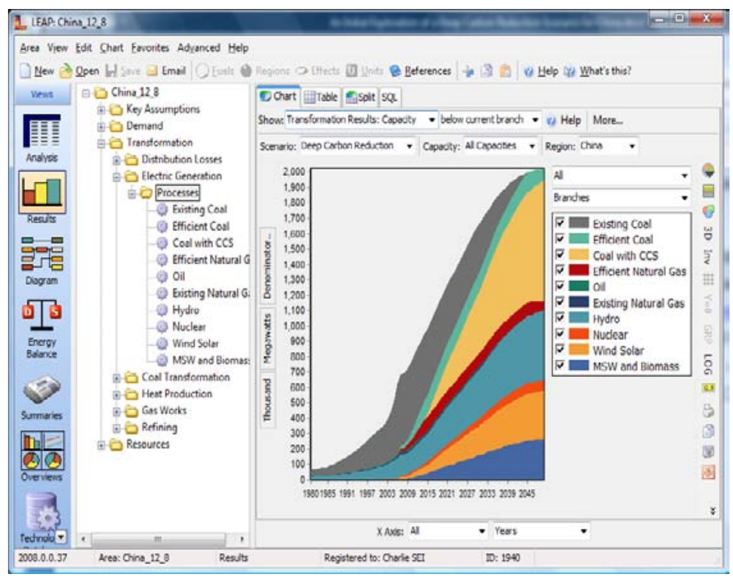

Figure 1: The LEAP Software System

3 A Baseline Scenario

The Baseline scenario (BLS) examines how China's energy system and its CO_2 emissions might evolve to 2050 in the absence of significant new policies specifically designed to address climate mitigation. The BLS covers energy consumption and production and related CO_2 emissions going back historically from 1990 to 2006 and projecting forward to 2050.

The analysis uses a straightforward accounting methodology in which emissions of different pollutants are calculated as the product of fuel combustion and an emission factor. Energy consumption is in turn calculated as the product of an activity level measuring the level of energy service provided (e.g. number of households, passenger-km of transportation, dollars of value added in an industry, etc.) and an energy intensity. Put simply, emissions are calculated as follows:

P = A x E x F

Where:

P is the emission of CO_2
A is a measure of economic activity
E is energy intensity of the activity [TJ/activity]
F is the CO_2 emission factor [Tonnes/TJ]

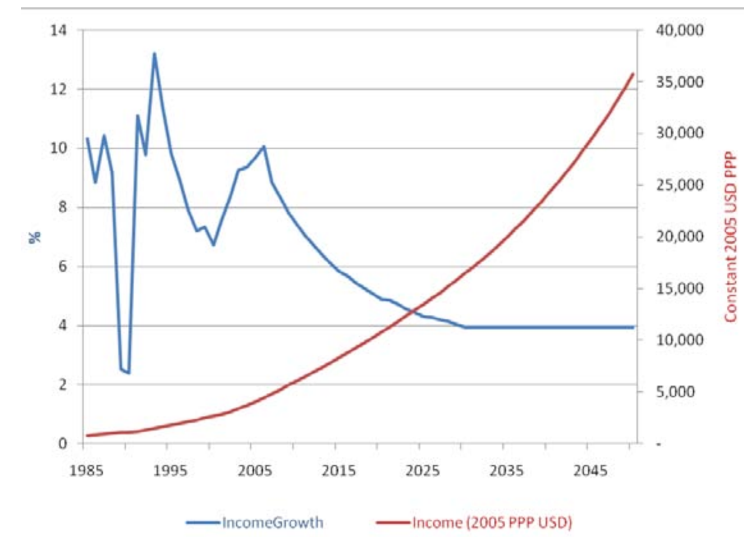

Figure 2: Baseline Average Income and Income Growth

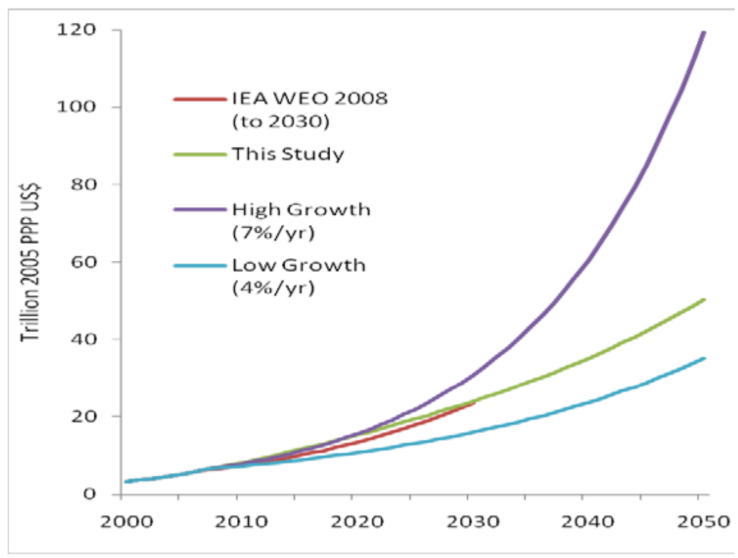

Figure 3: China GDP Sensitivity to Growth Assumptions

Levels of activity in each consuming sector (industry, households, services, agriculture, transport) are first projected forward based on overall assumptions about levels of growth of the Chinese economy and how its structure might shift (e.g. from industry to services, or between heavy and light industry) as income levels grow.

The scenario is driven forward by two high level exogenous assumptions: population and average income levels. For population, the medium variant of the United Nations population projections is used [3], which foresees China's population peaking in 2030 at 1.46 Billion people before declining slightly to 1.41 Billion in 2050. Average income levels are assumed to continue to grow rapidly in China (although somewhat slower than in the last two decades) as shown in Figure 2. Historical income levels are taken from the World Bank World Development Indicators, 2008 [4] expressed in constant 2005 US$

purchasing power parity (PPP) terms[1]. After 10.1% growth in average income levels in 2007 the scenario assumes that growth declines gradually to 4% in 2030 and thereafter. The assumption is that rapid development will continue but as China's economy matures and the size of its workforce peaks, its rate of growth will also decline. The net result of these assumptions is that average income levels grow enormously from $4,062 in 2005 to $16,487 in 2030 and $35,711 in 2050, an increase of almost 800% and a value roughly equal to present day income levels in richer European countries such as the UK, Germany, France and Scandinavia.

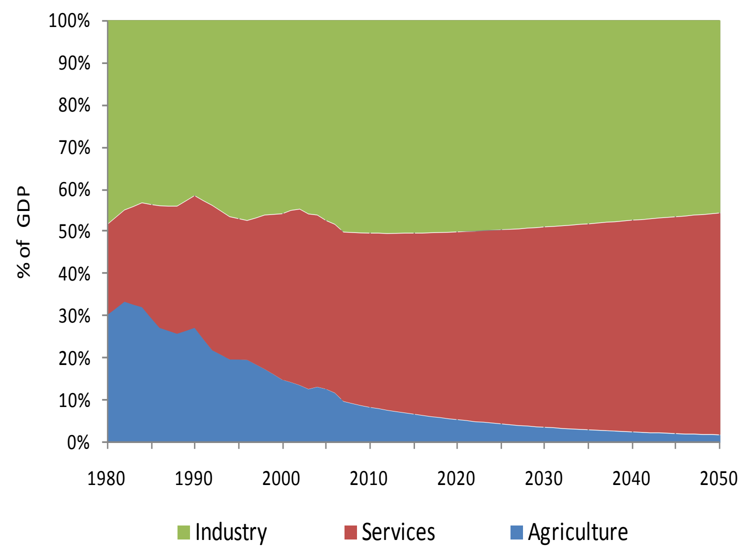

Figure 4: Historical and Baseline Value Added Trends

GDP is calculated as the product of population and average income so that the above assumptions also imply that China's GDP in PPP terms increases from $5.3 Trillion in 2005 to $24 Trillion in 2030 and $50 Trillion in 2050. By comparison, US GDP in 2005 was about $12.4 Trillion. Figure 3 shows some sensitivity analyses of GDP projections under alternative assumptions about income growth.

GDP is initially separated into its sectoral value added components (industry, services and agriculture) using historical data from the World Bank. Industry is further broken down within the manufacturing subsectors. Here, data from UNIDO [14] is used to calculate historical value added in each major manufacturing sector corresponding to the sector groupings used by the IEA [15] for its industrial energy use statistics (iron and steel, chemicals and petrochemicals, non-ferrous metals, non-metallic minerals, machinery, food & tobacco, paper pulp & print, textiles & leather, transport equipment, wood & wood products, and "other").

[1] Unless otherwise stated, all monetary values in this memo are in units of constant PPP 2005 US$.

These historical data are used to calculate the share of value added in each major sector and subsector so that the estimates of GDP can be allocated down to the various energy consuming sectors and subsectors of China's economy. Future estimates of these activity levels are calculated based on the overall future growth in GDP coupled with cross-country regressions that estimate how the value added share of GDP from the industry, services and agriculture sectors are likely to change in the future as average incomes increase. In the baseline scenario, the share of GDP coming from services is projected to increase from 40% in 2005 to 52% in 2050. The share from agriculture decreases markedly from 12.6% in 2005 to only 2% in 2050. The balance (the share from industry) stays almost constant going from 47.5% in 2005 to 46.3% in 2050 (Figure 4).

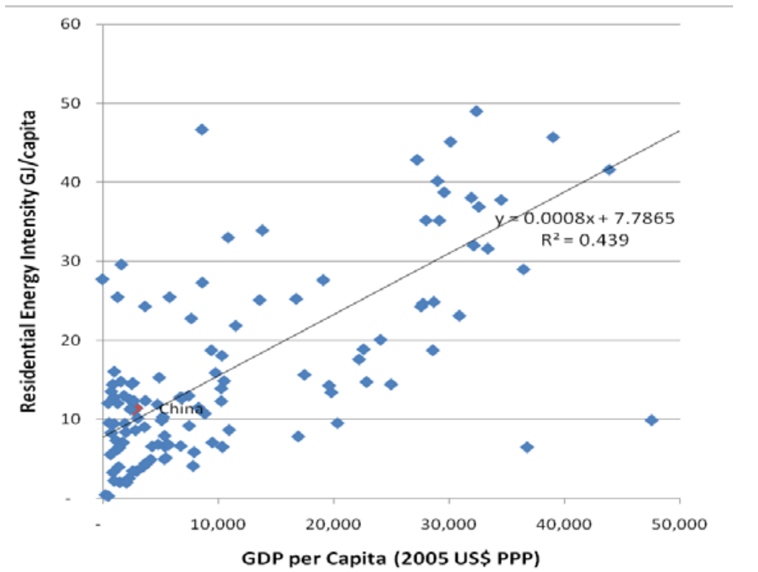

Figure 5: Income vs. Household Intensity in 2000 for various countries

These activity levels are multiplied by energy intensities that are initially calculated from historical data on energy consumption from the International Energy Agency [5], and which contains information on fuel use in all major energy consuming sectors. The intensity values are calculated by dividing IEA's total consumption data by each sector's historical activity levels. Energy intensities are projected forward based in part on an assessment of historical trends as well as cross-country comparisons of how energy intensities in each sector have evolved as incomes increase, adjusting for temporal improvements in energy intensities that can be expected due to autonomous energy efficiency improvements. For example, Figure 5 shows how energy use per capita in the household sector is correlated with income level across countries for the year 2000. These regressions inform a level of energy intensity that China is assumed to gradually converge towards as its average income levels approach those seen in the richer countries. This type of "convergence algorithm" was used for estimating future intensities in the household, services and agriculture sectors. A key benefit of this approach is that future energy intensities can be driven by overall assumptions on income growth – making it possible to do sensitivity analysis of different assumptions of GDP growth. Future energy intensities in the industry and transport sector are based primarily on historical trends as well as the Chinese Government's stated plans for the period to 2010.

In the transport sector, historical data on energy use are again taken from the IEA's energy statistics, which are broken down into passenger and freight energy use and major mode (road, rail, air, water and pipelines). Historical data on passenger transportation demands in passenger-km (p-km) and freight transportation demands in tonne-km (t-km) are taken from the China Energy Data book [6] prepared by the Lawrence Berkeley National Laboratory (LBNL), which in turn is based on China's National Statistical Yearbook [7]. These data are used to calculate historical energy intensities per pass-km and per tonne-km respectively. Activity levels are projected forward using GDP growth rates and the overall elasticities of passenger and freight transport with respect to GDP. Modal shares are projected forward informed by trends in the shares in recent years as well as typical values seen today in OECD countries.

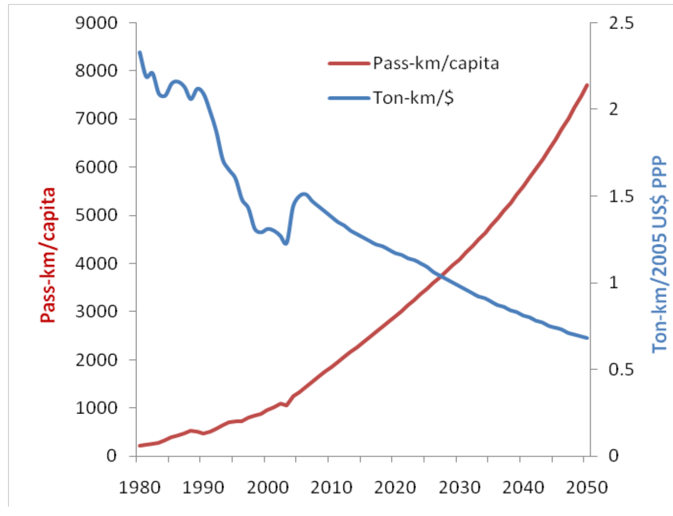

Figure 6: Transport Demand Trends in the Baseline Scenario

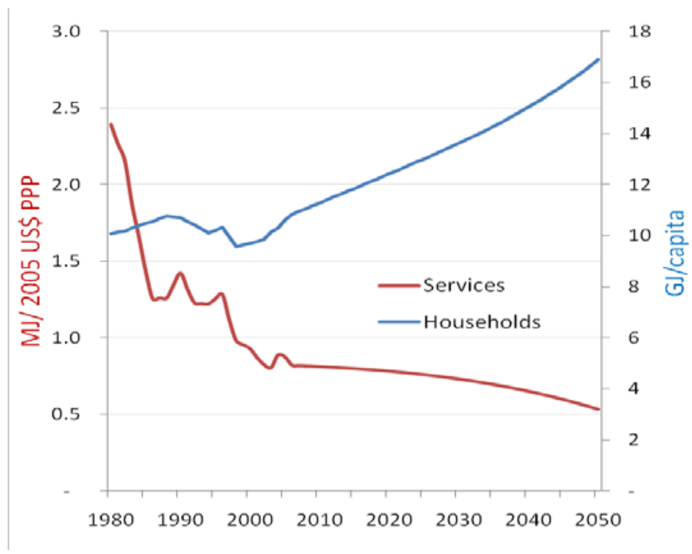

Figure 7: Baseline Household & Service Sector Energy Intensities

Both passenger and freight transport show huge growth in the baseline scenario with total passenger transport growing by a factor of more than 6 from 1.7 trillion p-km in 2005 to 11 p-km in 2050. Total freight transport grows by a factor of more than 4 from 8.0 trillion t-km in 2005 to 34 trillion t-km in 2050. While these levels of growth rates appear extremely high, it is worth noting that the levels reached trends in transport demand per capita (for passenger travel) and transport per unit of GDP (for freight) as shown in Figure 6 remain well below those in OECD nations today.

Passenger transport demand per capita grows from 1325 p-km per capita in 2005 to 7710 p-km/capita in 2050, which is still lower than current values for all OECD nations [IEA, 2007]. Transport freight requirements per dollar actually declines in this scenario from 1.5 t-km/$ in 2005 to 0.68 t-km/$ which is similar to the current values in large OECD nations such as the US, Australia and Canada, but still significantly higher than the average for OECD nations of about 0.4 km/$. Such a decline in freight transport per dollar of value added is to be expected given the gradual shift from heavy industry to services and lighter industries seen in the scenario.

Nevertheless, the huge absolute levels of growth do call into question the plausibility of the baseline assumptions. In other words, it is questionable whether China can really improve its transportation infrastructure sufficiently by 2050 to support the huge increases in transportation projected in these scenarios.

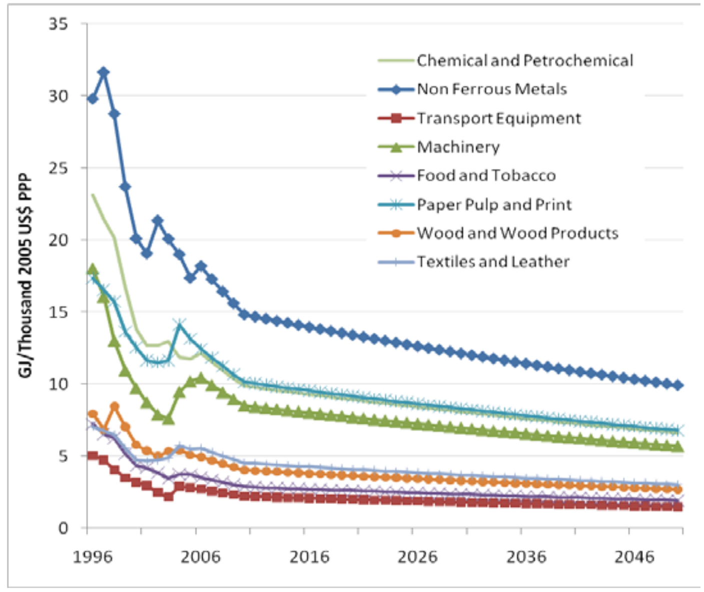

Figure 8: Manufacturing Energy Intensities

Historical and baseline energy intensity trends in the service and household sectors and in various industrial manufacturing sectors are summarized in Figure 7 and Figure 8. Service and industrial energy intensities are projected to decline to 2050, continuing the historical trend but at a slower rate. On the other hand, household intensities are forecast to increase in the baseline scenario, a consequence of increasing average income levels.

Within each major sector and most major industrial sectors, fuel shares are calculated for the historical period (1980-2006) and then projected forward to 2050 using an assessment of past trends and a review of the particular circumstances and the suitability and availability of fuels in each sector. For example, in the household sector increases in average income are likely to be accompanied by a strong shift away from biomass fuels and coal and increased use of electricity and other modern fuels.

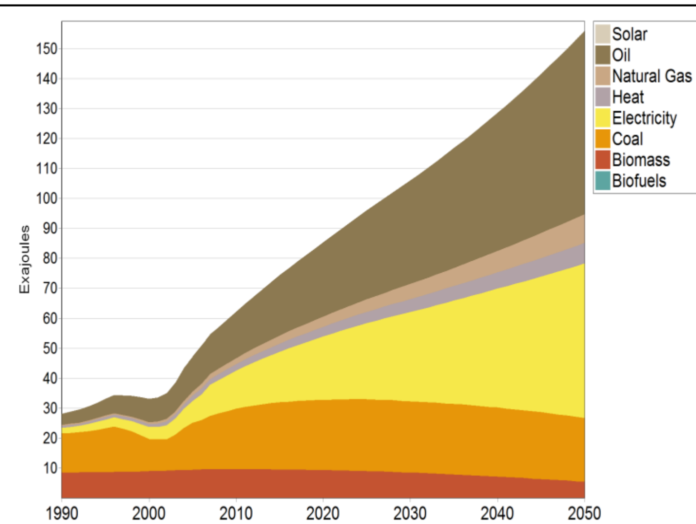

Figure 9: Baseline Final Energy Demand by Fuel (EJ)

Additional analysis was done to examine trends in two of the most important energy intensive sectors: iron and steel and cement. Aggregate historical data on fuel consumption for these sectors from the IEA [5] were calibrated against physical production statistics (tonnes of steel, tonnes of cement), data on types of production (BOF vs. EAF for steel, types of kilns for cement) and data on energy intensities and feedstock fuels for each different type of production from China's national statistics [20], and elsewhere [22].

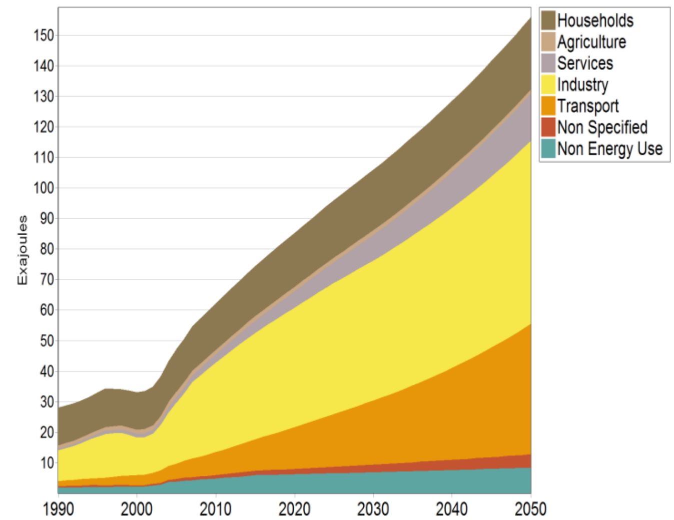

Figure 10: Baseline Final Energy Demand by Sector (EJ)

Projections of future energy consumption in the baseline sector were based on expected future changes in processes, energy intensity improvements, and projections of future steel and cement production in the country. Here a couple of important trends that have an important bearing on future energy consumption and GHG emissions are worth noting. First, the high rates of growth of production of steel and cement are assumed to abate after about 2025 with only modest growth seen thereafter. This agrees with the projections of other researchers in the field [23, 25] and reflects an assumption that as China's economy matures its requirements for these basic physical products peaks. Similarly, for iron and steel it is assumed that as China's economy matures so the availability of steel scrap will increase, so that by 2050 China can make much greater use of (EAF) furnaces, with consequent reductions in the use of the more energy and carbon intensive Basic Oxygen/Blast Furnace (BOF) technology. Reflecting this, EAF production as a share of total steel production is assumed to grow from 13% in 2005 to 50% in 2050. EAF production has an energy intensity of around 8 GJ/Tonne compared to 20 GJ/Tonne for BOF/Blast Furnace production [IEA, 2007b], in part because it can use steel scrap as a feedstock, thus avoiding the need to produce pig iron from ore.

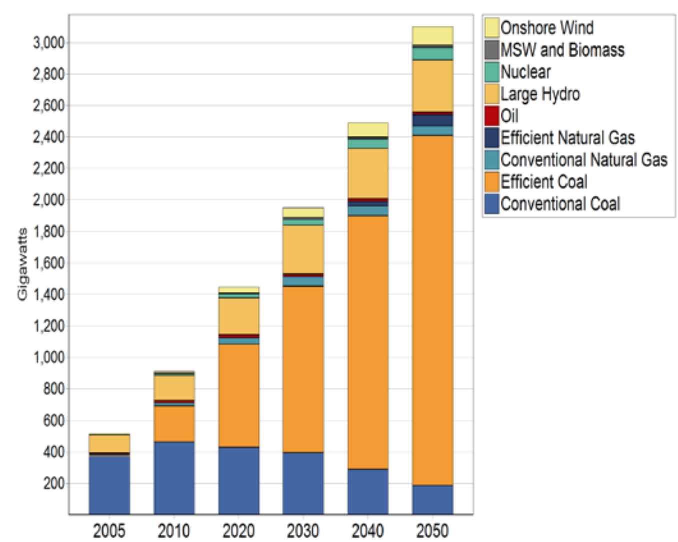

Figure 11: Baseline Electric Generation Capacity

In the cement sector, based on trends to 2030 described in McKinsey [23], a gradual phase-out of the more energy intensive types of kilns (wet process and vertical shaft kilns) is assumed, so that advanced dry process pre-calciner kilns achieve a market share of over 90% by 2050. Similarly, a gradual decrease in the clinker content of cement is assumed as clinker quality improves and more high quality substitutes become available (granulated blast furnace slag and fly ash). Dry process cement has a significantly lower production energy intensity of about 3 GJ/Tonne of cement compared to the now largely obsolete wet process kilns (6.4 GJ/Tonne) and vertical shaft kilns (5.7 GJ/Tonne), the latter of which still accounted for 47% of China's cement production in 2005 [IEA 2007b].

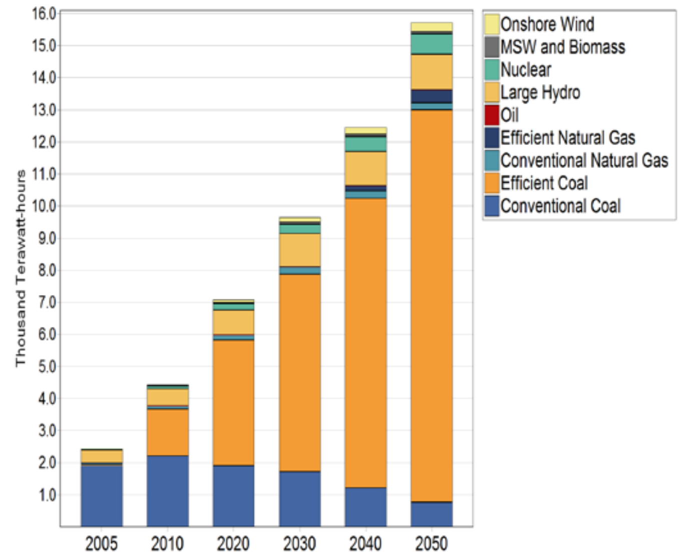

Figure 13: Baseline Electricity Generation

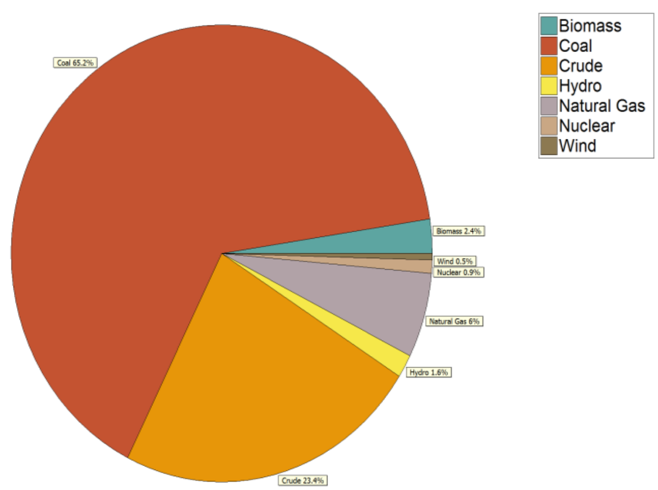

Figure 12: Baseline Primary Energy Requirements in 2050

The final energy demands in the baseline scenario are summarized in Figure 9 and Figure 10 showing historical data and projections for energy demand by sector and by fuel for China as a whole and broken down into various key sectors. Notice the increasing importance of electricity and oil products and the continued importance of coal, and the continued dominance of the industrial sector and the rapid growth in the transport sector.

In terms of energy supply, the analysis focuses on likely trends in the electric sector as shown in Figure 11 and Figure 12. Historical data on conversion technologies are taken from the IEA's world energy balances [5] and the China Energy Data Book [6]. Future trends in terms of generating efficiencies and the expansion of capacity are based the IEA's World Energy Outlook 2008 [1] as well as characteristics for various technologies described in the IEA's Energy Technology Perspectives Report 2008 [7]. Potential penetration rates for various renewable technologies are adapted and extrapolated from baseline estimates in McKinsey and ERI [23]. In the Baseline, total capacity expands from 516 GW in 2005 to 3116 GW in 2050 – equivalent to an annual rate of addition of 58 GW/year - very high, but similar to rate of additions in the last decade. Over the scenario period coal's share of capacity actually increases slightly from 72.3% in 2005 to 77.3% in 2050. Nuclear power also increases from 1.3% to 2.6% and renewables (primarily wind) increases from 0.2% to 4.8%. Hydro power decreases from a high of 22.7% in 2005 to 10.7% in 2050.

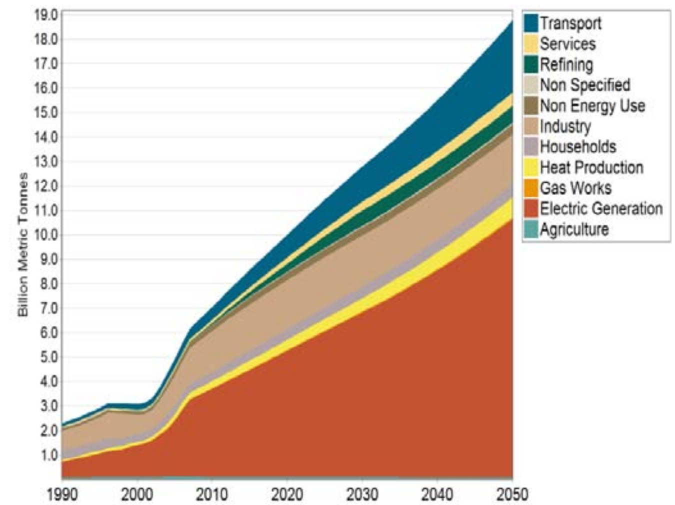

Figure 14: Baseline CO2 Emissions from Energy

Significant progress is seen in reducing transmission and distribution losses. New additions to power generation are expected to be significantly more efficient than the current average stock even in the baseline scenario, and are dominated by more efficient coal power plants as well as new additions of natural gas, hydro and nuclear power plants. Renewable generating technologies are expected to grow as well, although not enough to gain a substantial share of generation. Carbon capture and storage is not expected to gain any significant share of generation in the baseline scenario.

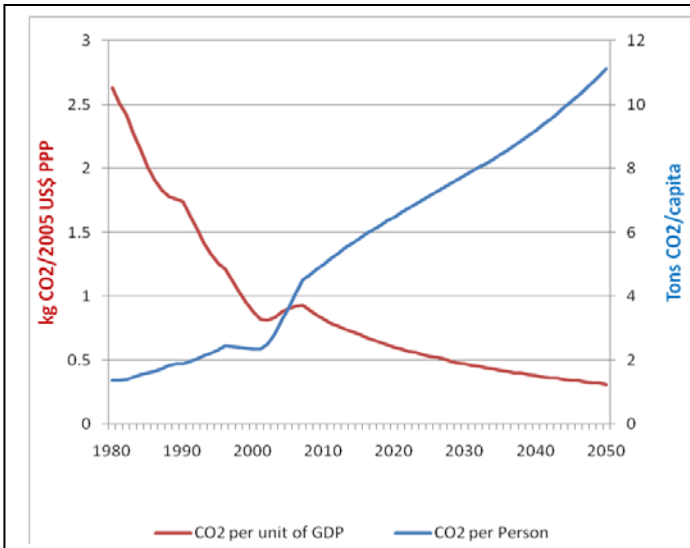

Figure 15: Baseline CO2 Intensities

As shown in Figure 13, primary energy requirements grow from 74.1 EJ in 2005 to 172 EJ in 2030 and 254 EJ in 2050. Coal continues to be the dominant energy form with its share of total primary requirements staying almost unchanged at about 65%. The importance of biomass declines as its traditional use in households gradually wanes. Crude oil gains in importance due to the rapid growth of road and air transport.

Emissions of CO_2 are estimated by applying standard IPCC Tier 1 emissions factors wherever a fuel is combusted in the system. The emission factors are specified in terms of metric tonnes of CO_2 per Terajoule of fuel being combusted. Thus, while the factors are approximate they do capture the variation in the energy content of fuels being combusted in China.

Energy sector CO_2 emissions, shown in Figure 14 increase from 4.8 GT CO_2 in 2005 to 12.3 GT in 2030 and 18.9 GT in 2050. By 2050, electric generation is by far the leading source of emissions although industry and transport are also important.

Emissions intensities per capita shown in Figure 15 increase from 3.6 t/cap in 2005 to 7.8 t/cap in 2030 and 11.1 t/cap in 2050, which is only 58% of US levels in 2005 (19.6 t/cap), but higher than those of Sweden in 2005 (5.64 t/cap).

Emissions intensities per dollar of GDP continue to decrease although more slowly than in recent decades, declining from 0.9 kg/$ in 2006 to 0.47 kg/$ in 2030 and to 0.31 kg/$ in 2050. These figures can be compared to the equivalent 2005 figures for the USA and Sweden of 0.47 kg/$ and 0.18 kg/$ respectively, showing on the one hand considerable improvements over the period but also showing the potential for much greater declines.

4 A Deep Carbon Reduction Scenario (DCRS)

The DCRS is intended to explore the feasibility of massively reducing China's CO_2 emissions in 2050: with energy sector GHG emissions reduced to about 32% of their 2005 values or about 90% below the 2050 levels projected in the Baseline scenario, with a goal of achieving levels of emissions in China that are compatible with the GDRs *global emergency pathway* under the same demographic and macroeconomic trends as in the Baseline scenario.

In one respect, the DCRS is much more ambitious in terms of its CO_2 reductions goals than other recent global energy scenarios. For example both the *Blue Map* scenario of the IEA's recent Energy Technology Perspectives report [7] and the recent GreenPeace *Energy Revolution* scenario [24] both aim for reduction in CO_2 emissions of about 50% versus 2005 levels or about 80% versus the expected 2050 values in their Baseline scenarios. The DCRS for China has more ambitious goals because it is designed to be compatible with the overall emissions reductions pathway of the GDRs framework that aims for global reductions of about 82% versus 2005 levels.

In this section, the measures included in the DCRS that enable it to achieve these ambitious goals are described in more detail. Estimates of mitigation potential were developed based on a sector by sector review of options available in each sector. Due to the constraints of this study, these drew in large part from existing studies for China, most notably those developed in studies by McKinsey [23] and the IEA [7].

The DCRS focuses primarily on mitigation technologies that are either already commercialized or are expected to become commercialized in the next decade, in time that their deployment will have a significant impact in reducing China's emissions.

Note however, that particularly for the period after 2030, the DCRS assumes that energy intensities will continue to decline rapidly, which inevitably implies a massive and sustained levels of research and development on a global scale.

The main mitigation measures included in the DCRS are described in the following sections.

4.1 Buildings

The buildings sector has huge potential for mitigation of CO_2. Not only can energy intensities be reduced dramatically but the sector can also be largely decarbonized by replacing direct use of fuels with greater use of electricity, heat, and solar energy. Energy intensity reductions can be achieved through measures including: improved design of new buildings to incorporate passive heating and cooling principals, retrofitting of existing building shells to reduce heating and cooling loads, the installation of more efficient HVAC systems, the use of efficient lighting, the introduction and enforcement of stringent appliance efficiency standards for refrigerators, washing machines, dryers, TVs etc., and improvements in the construction of buildings (e.g. to use more sustainable and less energy intensive building materials). Of these measures, improved new building design likely has the largest long-term potential and the best economic benefit-cost ratio. Because China is developing so rapidly and building construction is at such a high level, this area clearly presents a huge opportunity. However, rates of construction are expected to decline in the latter part of the scenario as China's population peaks, its workforce ages and its economy matures. Thus, time is short to implement such measures and avoid large "lock in" effects. Implementing efficient new building designs will require wholesale retraining of architects and engineers and policy changes at the highest level to require that these new types of buildings become the norm. Failure to act quickly will mean that greater numbers of buildings will eventually have to be retrofitted for energy efficiency: an approach that is more costly and provides less emissions reduction.

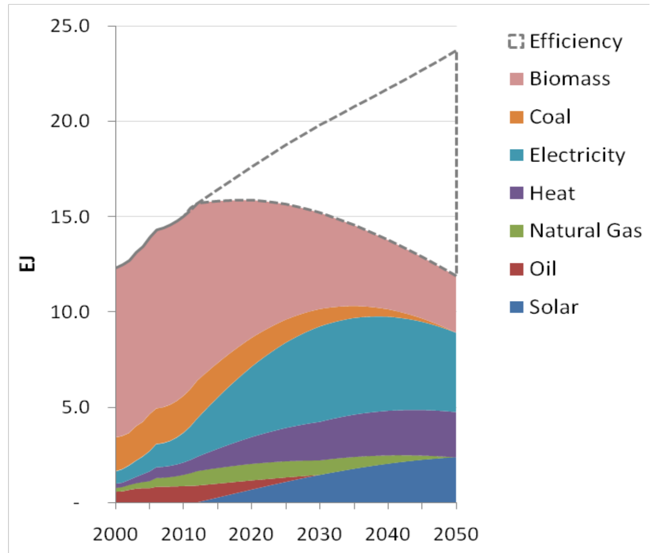

Figure 16: Household Energy Demand in the DCRS (EJ)
Savings vs. Baseline shown as "efficiency"

In China, a proper assessment of energy and GHG emissions reduction potential in the buildings sector requires a detailed end-use analysis of energy consumption in the both the household and services sectors, considering the most important energy end-uses: space heating and cooling, water heating, cooking, lighting and appliances. This would need to account for the differences between urban and rural households as well as the various climatic regions which affect heating and cooling demands. In the service sector, the differences between major service sectors (offices, hospitals, shops, restaurants, hotels, government buildings, etc.) also need to need to be considered. Such a detailed assessment went beyond what was possible in this study. So for the DCRS a simpler approach was used: first adopting an approximate estimate of the potential for energy intensity improvements, and then combining this with a judgment of the potential for fuel use shifts in each sector. A number of studies cite the technical potential for energy efficiency reductions to be as high as 80% in the buildings sector in OECD countries [7] and given the importance of space heating in China (estimated by the Lawrence Berkeley laboratory to be over 50% of final residential energy demand in China [18]) and the poor energy efficiency of its housing stock, a similar target is also likely to be possible in China. However, given the lower average incomes levels of China vs. OECD countries, a lower target of 50% reduction in the 2050 energy intensity vs. the baseline has been assumed for the DCRS.

As a result, per capita energy intensities for the household sector decline from 10.6 GJ/capita to 8.4 GJ/capita in the DCRS instead of growing to 16.9 GJ/capita in the Baseline scenario. This fairly modest rate of reduction of 0.68%/year from 2005 to 2050 reflects the initial low level of energy use per person in China in 2050 compared to the values more typical in OECD countries (between 15 GJ/capita for Sweden and 41 GJ/capita for the US, normalized to 2700 Heating Degree Days).

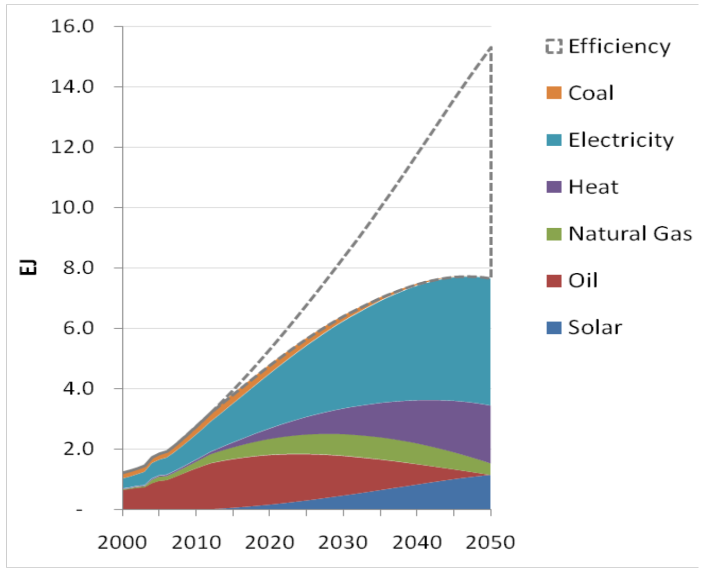

Figure 17: Services Energy Demand in the DCRS (EJ)
Savings vs. Baseline shown as "efficiency"

In the service sector, energy intensities per dollar of value added decline more rapidly at 2.1%/year from 2005 to 2050 from 0.87 MJ/$ in 2005 to 0.3 MJ/$ in 2050. China's intensity in 2005 is very similar to the current OECD average value of about 0.9 MJ/$, although these values are very hard to interpret given the difficulties associated with using value added as a measure of activity in this sector, particularly for 2050.

The mitigation benefits of these energy intensity improvements are further magnified through a shift in the fuels used in the buildings sector: with a nearly complete shift away from coal, oil and natural gas in favor of electricity, district heating, and solar energy (the latter primarily for hot water production). As will be seen later, this shift away from small scale combustion of fuels is coupled with a dramatic decarbonization of electricity and heat production (described later). Biomass fuels, which according to IEA statistics in 2005 still accounted for more than 60% of final energy consumption, are expected to rapidly decline in the Baseline sector as rural incomes improve. But in the DCRS a significant level of biomass fuel use is retained – reflecting the development of cleaner, more efficient and more convenient ways of utilizing biomass fuels in rural households. In the service sector the DCRS similarly sees the potential for the near-complete phase out of fossil fuels, replaced by electricity, heat and (to a smaller extent than in the Residential sector) solar energy.

The net results are displayed in Figure 16 and Figure 17 showing the final fuel demands in the household and residential sectors in the DCRS versus the Baseline scenario. The reduction between the two scenarios is displayed as "efficiency".

4.2 Transport

In terms of passenger transportation, the DCRS reflects the implementation of three substantial shifts in transportation policy:

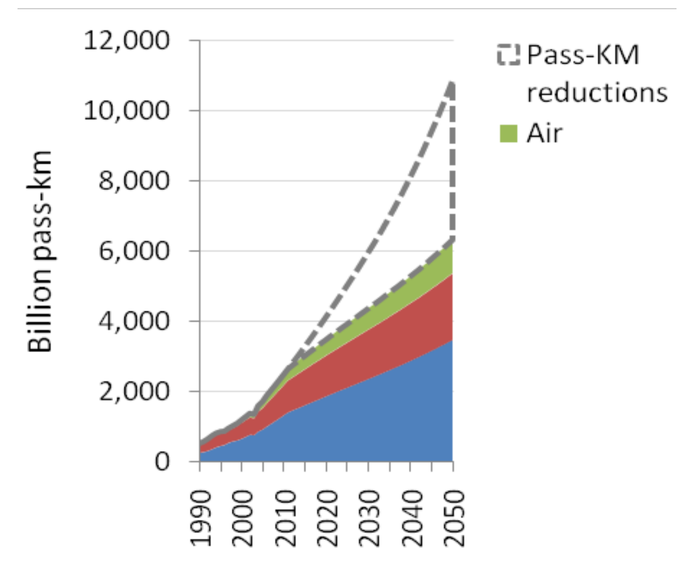

Figure 18: Passenger transport modal shares in the DCRS

1. Firstly, the DCRS reflects policies to slow the rapid overall growth in passenger transportation. In the Baseline scenario the overall demand for passenger-km grows by a factor of 6.3 from 1.7 to 10.9 trillion pass-km. The DCRS assumes a range of policies such as increased fuel pricing, better urban planning to reduce the need for commuting, congestion charging, a revitalization of cycling, parking restrictions, restricted airport developments, etc. Taken together, these policies are assumed to reduce the overall growth in passenger-km to a factor of "only" 3.7, resulting in an overall demand for 6.3 trillion pass-km in 2050. It is worth noting that apart from its GHG benefits, such policies would also yield innumerable benefits in terms of the livability of China's cities (reduced pollution, less congestion, fewer traffic fatalities). Indeed it is questionable whether China would be able to develop the infrastructure that would be required to meet the huge levels of transport growth envisaged in the Baseline scenario.

2. Secondly, the DCRS assumes shifts in modal shares relative to the baseline scenario. The baseline assumes a continued shift towards the North American model for passenger transportation – founded upon private cars. In the Baseline, road as a share of total passenger-km increases from 53% in 2005 to 70% in 20250 – a level still well below the OECD average of about 80%. In the DCRS, road transport as a share of total passenger-km is assumed to stay roughly constant even as the total passenger-km value grows enormously – by a factor of 3.75. The share of road transport made up by buses is not modeled explicitly but is also assumed to stay roughly constant. Similarly, the rail share of passenger-km is assumed to decrease only slightly from 34.8% in 2005 to 30% in 2050. This represents a huge increase in absolute terms from about 606 billion pass-km in 2005 to about 1900 pass-km in 2050. This would be an enormously high value for a developed nation but is not unprecedented. In terms of shares it is close to the 29% rail share seen in Japan in 2004. The share for air travel, both domestic and international increases from 11.8% in 2005 to 15% in 2050, below the 18% reached in 2050 in the Baseline scenario. Figure 18 summarizes points 1 and 2: showing the overall decrease in passenger-km in the DCRS compared to the baseline and transition of modal shares in the DCRS.

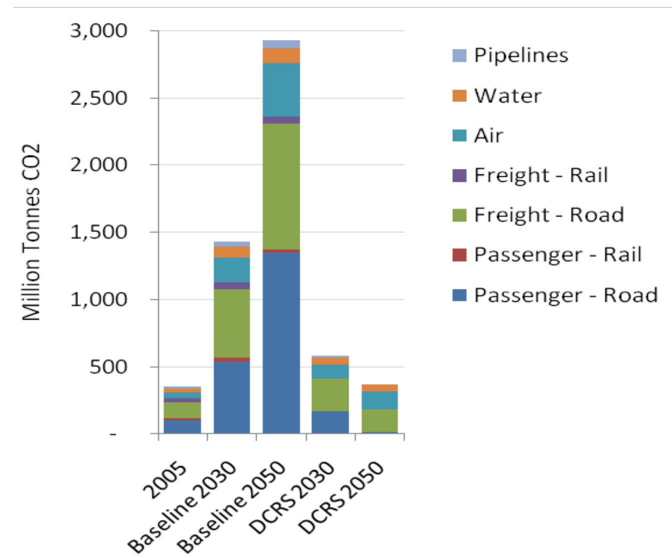

Figure 19: DCRS and Baseline Transport CO_2

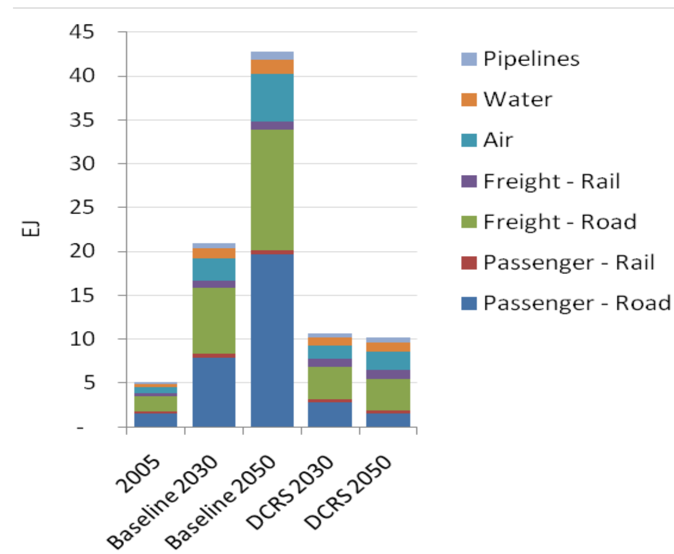

Figure 20: DCRS and Baseline Transport Energy Use

3. Thirdly, and perhaps most challenging of all, the DCRS assume a massive shift away from dependence on oil-based internal combustion engines toward complete electrification of

passenger road transport. Such a transition could happen in a number of ways but will likely follow a gradual path through hybrids and plug-in hybrids to fully electric vehicles. In the DCRS this is modeled as a gradual transition starting slowly in about 2015, ramping up after 2030 and culminating in 2050 with 90% of all road passenger-km being delivered by electrical vehicles. While extremely challenging, such a pathway does seem possible if one takes an optimistic view about the development of the necessary technologies (most importantly the ability for advanced battery technologies to come down in cost) and of course about the development of the political will at the highest level (internationally, not just within China) to enable such a massive transition. The transition from oil to electricity not only yields a significant decarbonization of transport, it also yields important efficiency benefits. Energy requirements of full electric vehicles per passenger-km in the DCRS are based on estimates in Mackay [32] and equal roughly ¼ of the energy requirements of gasoline vehicles.

Similar but much less dramatic transitions are assumed for freight transport. Specifically, because of the assumption of the same levels of GDP growth in both the Baseline and the DCRS it is assumed that the overall levels of freight transport in ton-km are equal in both scenarios. The decline in the modal share of rail freight expected in the Baseline is assumed to be arrested in line with policies to promote rail over road transport so that the modal shares for both rail and road stay roughly constant over the period to 2050. Finally, road freight is also assumed to begin a path toward electrification. However, this path is assumed to lag well behind the changes seen for passenger road transportation, so that by 2050 only 30% of road tonne-kms are delivered by electricity.

In addition to these fundamental shifts, the DCRS also assumes modest penetration of biofuels in the air travel and maritime sectors. Due to the current inefficiency of biofuels production, which yields few benefits in terms of lifecycle CO_2 emissions per liter of fuel (with the notable exception of biofuels produced from sugarcane) and the potential for creating competing demands between food and fuel, it is assumed that first generation biofuels do not gain significant market share in the DCRS. However, second generation biofuels produced from woody crops are assumed to become available in the middle of the next decade and are assumed to make a modest but measurable contribution in providing substitute fuels for water freight transport and to a lesser degree for air transport. The lifecycle CO_2 emissions profile of these second generation biofuels is still not clear, but for the purpose of this analysis we have tentatively estimated that they will emit half as much CO_2 as fossil fuels per GJ.

Finally, in terms of rail transport, both the Baseline and the DCRS assume the complete phase out of coal fired railways, while the DCRS also assumes a complete transition by 2030 to electric powered trains. The DCRS also assumes gradual efficiency improvements for rail travel due to the introduction of new technologies such as regenerative breaking.

The results of this analysis are shown in the accompanying figures. Figure 20 compares net final energy demand for 2030 and 2050 in the Baseline and the DCRS, while Figure 19 makes the even more noticeable difference in CO_2 emissions between the two scenarios.

4.3 Industry

In China, industry is the largest final consumer of energy, accounting for 55% of final energy consumption. As mentioned earlier, industrial energy demands are projected to continue rising in the Baseline scenario although significant growth in energy use in the heaviest industrial sectors is expected to come to an end after the late 2020s as China's economy matures. This trend combined with steady improvements in energy efficiency and a switching to less carbon intensive fuels result in CO_2 emissions declining after 2035 even in the Baseline scenario.

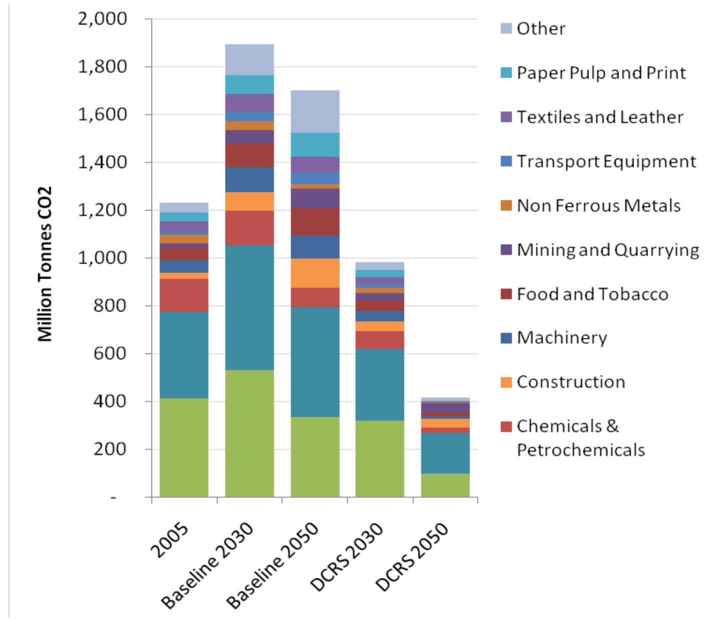

Figure 21: DCRS and Baseline CO2 Emissions (including cement process

The DCRS is assumed to further accelerate these trends through more concerted efforts to improve energy efficiency and switch to lower carbon fuels wherever possible. Two major sectors: iron & steel and cement were looked at in some detail, while for the remaining sectors, due to time limitations of this study, the analysis relied on simpler assumptions -- primarily that China will continue and accelerate its current efforts to reduce energy intensities. These assumptions need to be confirmed by further research but serve as a placeholder for now.

- **Iron and Steel.** In the iron and steel sector, large emissions reductions can be achieved if the use of electric arc furnaces (EAFs) for steel production can be more widely utilized. We assume in the DCRS that by 2050, EAF furnaces achieve a market share of 75% up from only 13% in 2005. Such a high share is today seen in only a few countries (e.g. Mexico, Spain, etc.), and will only be possible if sufficient scrap steel is available. Scrap supplies are generally seen as a function of the maturity of the economy. Given the current rapid development of China's economy and its expected maturation in the late 2020s, the required supplies of scrap steel may be possible but clearly this is an area that requires further research. Notwithstanding efforts to switch to EAF steel production, coal-based BOF/Blast Furnace production will inevitably remain important in China given the country's reliance on coal. Here, reductions in emissions will have to rely on energy efficiency improvements and carbon capture and storage. Based on a review of a variety of industry research [e.g. 26, 27] we assume energy intensity improvements of 30% (per ton of steel produced) by 2050 combined with carbon capture and storage for the CO_2 generated from 50% of BOF produced steel by 2050.

- **Cement:** The cement industry is of huge importance for CO_2 emissions and hence for CO_2 mitigation efforts. Energy use in the Chinese cement industry in 2005 produced 203 million metric tonnes of CO_2, roughly 17% of all industrial energy-related emissions. However, the cement making process (calcination) itself emits CO_2 when calcium carbonate ($CaCO_3$) is heated in kilns to form calcium oxide (CaO) and carbon dioxide (CO_2). These cement process emissions amounted to an estimated additional 518 million metric tonnes of CO_2 in 2005, adding an additional 42% to industrial CO_2 emissions[2].

  In the coming decades, a number of options may become available to reduce emissions from cement and these are reflected in the DCRS. They include a more rapid and complete switch to the less energy intensive advanced dry process pre-calciner kilns, further reductions in the clinker-to-cement ratio (to reduce the overall need for cement in concrete), the use of carbon capture and storage for up to 50% of cement kilns by 2050, and the limited use of low carbon agricultural residues or biofuels for co-firing of kilns. In the longer run a number of new technologies are being researched for the production of new “eco-cements” that could potentially reduce emissions even more dramatically. These include new magnesium (as opposed to calcium) based cements that are less energy intensive to produce and, while they also produce CO_2 during manufacture, most of this is reabsorbed from the atmosphere during setting and hardening [29]. Another concept involves the production of cement-like substances from the waste heat and flue gases of fossil fired power plants, in a process that mimics the way marine coral is produced [28]. All these processes are only design concepts at present. They will face significant hurdles before they can be commercialized, not least because cement quality is very carefully regulated for safety due to its use as a construction material. For these reasons, these new types of production process are not included in the DCRS even after 2040. Nevertheless, there is reason to think that cement production could be significantly decarbonized beyond 2050 and perhaps even before.

- **Other sectors:** As mentioned above, in all other manufacturing sectors (chemicals; non ferrous metals; transport equipment; machinery; food and tobacco; paper, pulp and print; wood and wood products; textiles and leather; other) energy consumption in the DCRS is projected using fairly simple placeholder assumptions that will require further in-depth analysis to confirm their feasibility. China is assumed to continue its intense efforts to reduce energy intensities. It has been aiming to reduce its energy overall intensity by 20% between 2006 and 2010, although at present, insufficient data is available to conclude if it will meet that goal. It is also worth noting that these goals are for overall energy intensity across all sectors of the economy – they are not a measure of technical improvements in a particular sector. So for example, a shift in the production of GDP from industry to services would yield a reduction in energy intensity (per dollar of value added) even if Chinese industry continued producing at its current technical intensity. Nonetheless, for the purpose of this analysis it is assumed that a significant

[2] Estimates of cement process emissions and other non energy sector sources and sinks have not been studied in detail, but preliminary estimates for the Baseline and DCRS scenario are included in the LEAP data set accompanying this paper.

proportion of the intensity reduction goal is met by genuine energy efficiency improvements in the industrial sector and that these reductions (assumed to be 2.5%/year to 2010) will continue albeit at a lower rate of 1.5%/year thereafter. This can be compared to the assumption of only 0.5%/year decrease in the Baseline scenario after 2010. The net result is that industrial energy intensities in 2050 in the DCRS are only 47% of their starting value in 2005. This assumption of a 53% reduction is clearly quite optimistic, but it is not without precedent, especially in China where IEA statistics suggest that, in the 25 years since 1980, energy intensities in the major industrial sectors other than cement and iron & steel have been reduced by between 50% and 89%. Of course these reductions may reflect the gathering of "low hanging fruit" and the benefits of economies of scale, which may be one-time gains that cannot easily be repeated, but it is at least possible that the reductions assumed in the DCRS can be engineered in the coming 40 years if the international political will emerges to do so.

Coupled with these assumptions on future intensity improvements, the DCRS examines the potential within each sector for fuel-switching to lower carbon fuels based largely on an acceleration of past trends to switch away from coal and oil and toward greater use of electricity and central production of heat. In two sectors - paper, pulp and print and wood and wood products the DCRS also assumes greater use of biomass and agricultural residues. Carbon capture and storage is not assumed to be viable in sectors other than the largest and most carbon intensive sectors: cement and iron and steel.

- **Dematerialization:** In addition to improvements in energy efficiency, there are a variety of opportunities for China to begin to pursue less material-intensive forms of development. Dematerialization implies that a larger fraction of GDP will come from services and light industry and a smaller fraction comes from the more energy and carbon intensive heavy industrial sectors. However such shifts might not necessarily imply genuine dematerialization – they might simply imply that *production* shifts away from China to other perhaps equally carbon intensive nations, whilst material *consumption* in China continues to increase. Such a transition would in fact be replicating how most OECD nations have grown in recent decades -apparently reducing their energy intensities, even while substantial amounts of production have been shifted oversees (much of it to China).

  Since the goal in the modeling the DCRS is to reflect a future for China that is genuinely compatible with an assumed global effort at climate protection, the DCRS does not include any structural shifts beyond those seen in the Baseline scenario.

  This is not to imply that dematerialization is not an important option for China. Indeed, many will argue that the task of providing growing welfare to society whilst consuming less is the key challenge for humanity in the 21st century. Nevertheless, the DCRS ignores this question, primarily because the intention with this analysis is to examine whether mitigation targets can be met at the same time as fulfilling China's existing development goals. Of course if China does succeed in meeting its development goals, so that by 2050 its per capita income levels are close to those of OECD nations today, it is also likely that OECD nations will have in the meantime grown considerably themselves. Thus, unless richer countries quickly take up the task of dematerializing their own economies it is hard to imagine that China will wish to do so.

4.3.1 Results for Industry

The overall results for industry are displayed in Figure 21 showing the final fuel demands in the industrial sectors in the DCRS versus the Baseline scenario, and in Figure 22 showing industrial sector CO_2 emissions including both energy related emissions and cement process emissions.

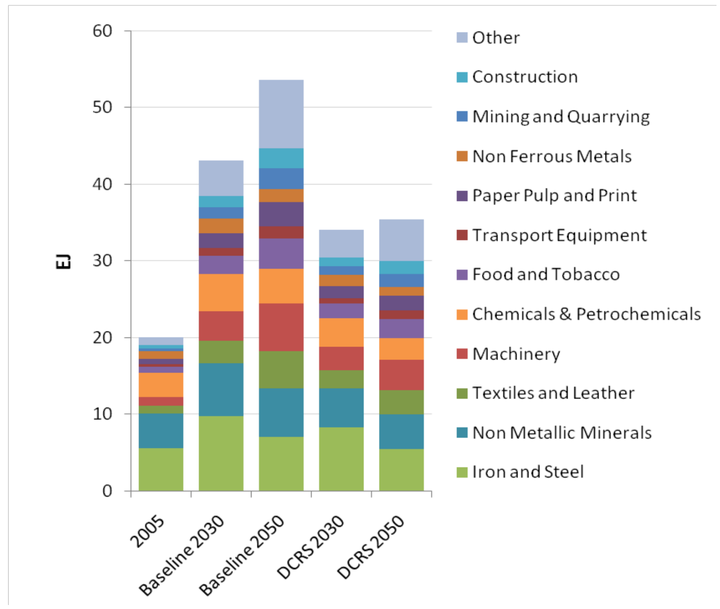

Figure 22: DCRS and Baseline Industrial Energy Use

4.4 Electric Generation

The fourth and perhaps the most difficult area for policy intervention in the DCRS is China's energy supply and more specifically its electricity generation sector. Here the DCRS models a massive undertaking to decarbonize the supply of electricity and heat to the extent possible given China's resource base. This pathway is designed to work in tandem with efforts on the demand side to eliminate the localized combustion of fossil fuels, replacing them with electricity and centrally supplied heat.

The requirements for electricity in both scenarios are actually quite similar. In the baseline, electricity requirements grow enormously from 2, 445 TWh in 2005 to 15,781 TWh in 2050. In the DCRS the savings from aggressive energy efficiency efforts and efforts to reduce transmission and distribution losses are partly counteracted by efforts to switch final consumption away from direct use of fossil fuels and towards electricity and heat, resulting in final requirements of 11,767 TWh in 2050.

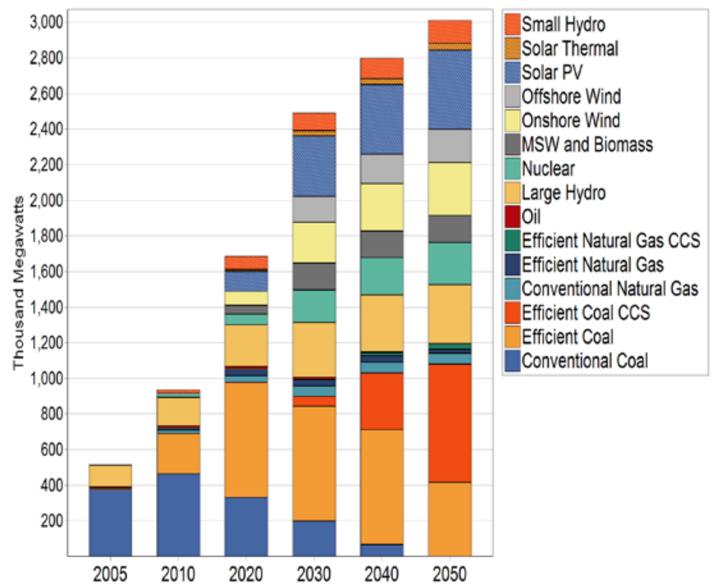

Figure 23: DCRS Electric Generation Capacity (GW)

The production of China's electricity and heat supplies is currently dominated by coal, which in 2005 accounted for 79% of electric generation. This share even increases over time in the Baseline scenario reaching 85% in 2050, albeit with a switch to more efficient types of power plants. The DCRS takes a very different path in three key respects:

1. **Early Retirement of Existing Inefficient Coal-Fired Electric Generation:** The DCRS assumes the accelerated retirement by 2045 of all existing coal and oil gas fired power plants. Since a large proportion of these plants were built in the current decade during China's most rapid phase of economic expansion, this represents a significant level of early retirement of capacity – an expensive proposition but essential for keeping China's CO_2 emissions within the overall budget specified for the scenario.

2. **Large-Scale Deployment of Efficient Coal Fired Power with Carbon Capture and Storage (CCS):** The DCRS assumes that all new coal plant build from 2010 onwards will be much more efficient than the current stock of coal fired power plants. The DCRS assumes an average efficiency of new coal plants of 43% versus the roughly 29% average efficiency of the current stock. Carbon capture and storage is assumed not to be available until 2020, but after that date all new power plants are assumed to use a CCS system that captures 90% of the CO_2 emitted by the plants. These plants are assumed to operate at a lower efficiency (39%) due to the energy needs of the CCS process. In addition by 2050, 90% of the existing power plants built between 2010 and 2020 are assumed to be retrofitted for CCS capture (which again entails a loss of efficiency). Smaller amounts of natural gas plants are also constructed and are subject to the same assumptions about CCS.

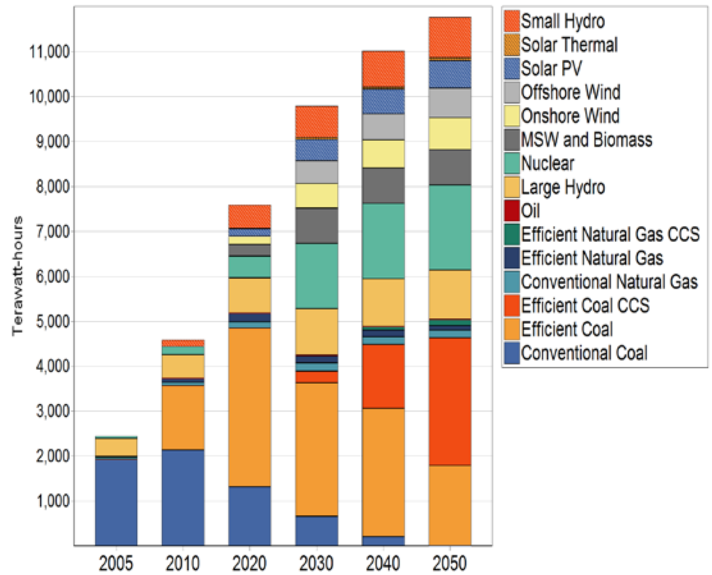

Figure 24: DCRS Electric Generation (TWh)

3. **Large-Scale Development of Renewables:** The DCRS also assumes that large amounts of new wind (offshore and onshore), solar (concentrating solar panels and solar PV), MSW/biomass and small hydro power plants are added. The estimates for these were based on a study by McKinsey [23] for 2030, with the added assumption that the potential capacity of these plants in 2030 could be expanded a further 30% by 2050. Given the growing resistance to large scale hydro power schemes, the capacity for these plants is assumed to be the same as in the Baseline scenario. Finally, the DCRS also foresees the potential for significant increases in nuclear power. While nuclear power is still deeply unpopular in large parts of the world due primarily to concerns over cost, safety, and nuclear proliferation, it has been included in the DCRS due to its potential for CO_2 mitigation and the demonstrated preference for this technology by policy makers in China.

4. **Combined Heat and Power Generation:** Apart from operating at greater efficiencies, the DCRS also assumes that all new thermal power plants are designed for the combined production of both heat and power. By 2050, 25% of all energy inputs to thermal and nuclear plants are assumed to be captured as usable process or district heat. This is likely to be hard to achieve, particularly since many power plants will be built away from the potential consumers of the heat. However this assumption is key in lowering emissions in the DCRS since it allows an essentially zero carbon resource (waste heat) to be used to meet the increasing need for energy in China's industrial sector as it simultaneously switches away from a reliance on carbon intensive fossil fuels. Such a scenario is only likely to be plausible if future industries and power plants are developed in a much more holistic and symbiotic fashion.

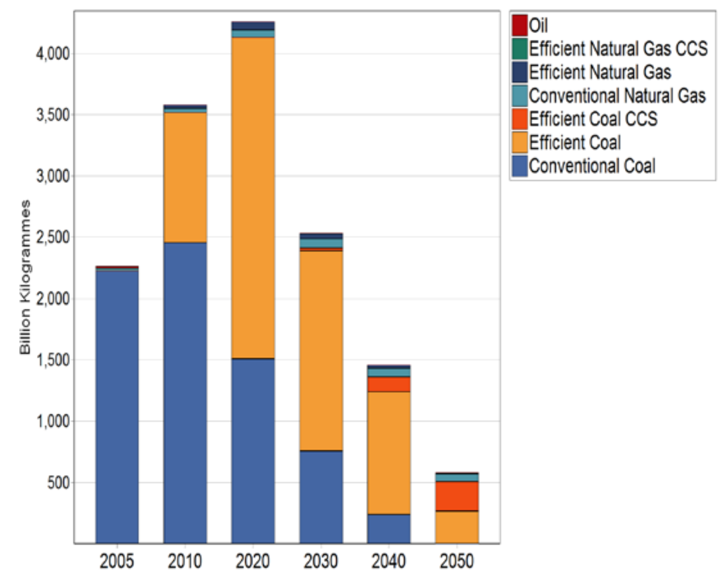

Figure 25: DCRS CO2 Emissions from Electric Generation

Figure 23 summarizes the capacity expansion path in the DCRS, while Figure 24 shows the level of generation from each type of power plant. Total capacity increases from 516 GW in 2005 to 3043 GW in 2050. Coal capacity triples from 373 GW to 1112 GW, while various types of renewable electricity (wind, solar, MSW/biomass and small hydro) increase from only 1.06 GW to 1,247 GW so that by 2050 they account for 41% of installed capacity. While this level of capacity is clearly unprecedented the numbers do at least lie well within the estimates of the available resources in China [8]. Nuclear power also increases more rapidly than in the Baseline - from 7 GW to 237 GW, reaching a share of 7.8% in 2050.

Figure 25 shows the overall results of the electric generation strategy in the DCRS: the sector is largely decarbonized with electric generation CO_2 emissions peaking in 2020 at 4.22 GT/year and declining thereafter to 0.60 GT/year by 2050. The CO_2 emissions remaining in 2050 are largely a result of the CCS process capturing only 90% of emissions, since by that date nearly all fossil-based power generation is assumed to be equipped with CCS. To keep emissions at this level and with this amount of power generation will require the capture of 60.0 GT of CO_2 between 2020 (when CCS is assumed to begin operation) and 2050. By 2050, CO_2 is required to be captured at a rate of 3.78 GT per year. In other words, even if CCS plants were expanded no further the total amount required to be captured over the next century would be approximately 249 GT CO_2. As yet there are no firm estimates of the potential CO_2 storage capacity in China. Storage options include coal seams, oil and gas fields, deep saline aquifers and ocean storage. A recent estimate by the Chinese institute of Soil and Rock Mechanics [quoted in 31] provisionally estimates the total geological storage capacity in China at 196 GT CO_2. If this estimate proves to be reasonably accurate, and assuming that power generation facilities can be sited conveniently to the storage sites, then the levels of CCS development in the DCRS could potentially be realized. However, CCS appears to be, at best, a stop-gap option unless ocean storage proves viable.

5 Overall Results

The result of implementing the four groups of measures in the buildings, industry, transport and electric generation sectors in the DCRS is shown in Figure 26.

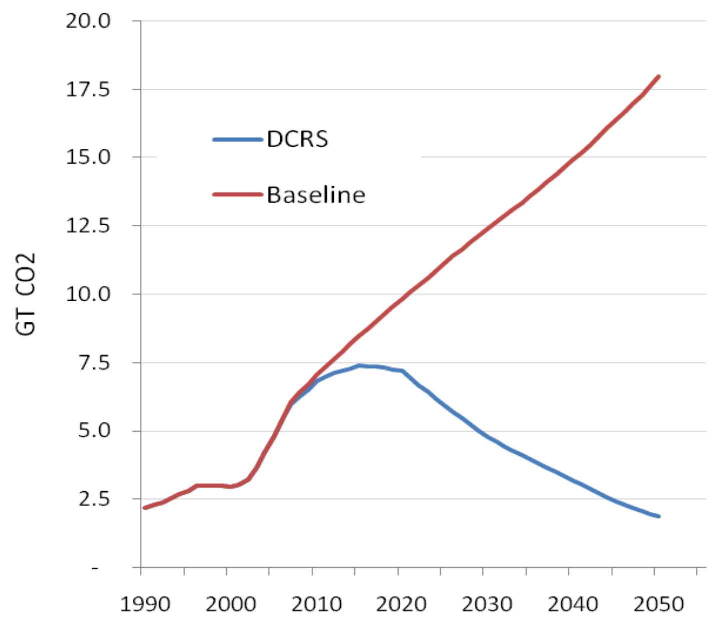

Figure 26: DCRS CO2 Emissions from Electric Generation

Total energy sector emissions are lowered dramatically compared to the baseline scenario. In 2050 the DCRS results in energy sector CO_2 emissions that grow from a base of 4.8 GT CO_2/year in 2005 and peak in about 2017 at 7.4 GT CO_2/year, before falling to 1.9 GT CO_2/year in 2050. Cumulative emissions between 2005 and 2050 are 229 GT CO_2: equal to the budget set for China by the GDRs framework and described in the introduction.

Annual CO_2 emissions intensities show a similar shaped curve, growing from 3.6 tons/capita in 2005, peaking in 2016 at 5.3 tons/capita then falling to only 1.3 tons/capita in 2050.

6 Conclusions

The previous sections provided an initial exploration of a scenario that would enable Chinese emissions to be reduced to a level that gives the world a reasonable chance of keeping global temperature increases below 2°C.

There are many uncertainties associated with such a scenario that require significant further research. In particular, the author has not yet developed an economic analysis of the costs and benefits of the scenario. In addition, many parts of the scenario require more in depth study. For example, more detailed analysis of the technical feasibility and the costs and benefits of alternative options are required in all sectors. As mentioned earlier, the data set associated with this analysis is being made available by SEI and it is hoped that other researchers, especially those in China will wish to improve upon it in due course and then share their findings with other researchers and the climate policy community.

In spite of the acknowledged limitations of this analysis, two key points so seem fairly clear:

- **All of the elements in the DCRS need to happen:** While the DCRS may be possible it can only be achieved if all of its elements are not just technically feasible but also economically and politically plausible. The DCRS is barely able to stay within the emissions budgets set through the GDRs framework and the loss of any single major element (the electrification of vehicles, the massive deployment of renewables, the complete switch to CCS based coal-fired generation, huge improvements in energy efficiency, significant changes to passenger transportation modes, etc.) would prevent a plan based on the DCRS from meeting its mitigation goals. It is of course possible that some important options that are available now, or that will become available in time to be implemented well before 2050, have not been included.

- **Time is short.** Not only do all of the options need to be implemented, but they need to happen quickly. Any delay in implementing options will make it almost impossible to meet the overall target budget of 230 GT CO_2. The DCRS is already very optimistic in the dates it assumes for the commercialization and deployment of key technologies. For example, it assumes that CCS starts being used commercially in 2020 and is fully deployed by 2050. Similarly plug in hybrid vehicles start gaining market share after 2015 and electric vehicles reach a market share of 90% by 2050. Any serious delay in this schedule will make the scenario's goal unattainable.

It is also important to recognize that other development pathways are available that can help meet the same climate protection goals. Such pathways would need to be much less materials intensive and would likely emphasize the provision of welfare more through the delivery of services than through the consumption of goods. For example, they might include less consumption of meat, more consumption of vegetables, better urban planning to reduce the need for transport, and more emphasis on health care and environmental protection. The net result of these measures would be a smaller industrial sector but a larger service sector with a consequent lowering of energy and GHG emissions. Just as with technical options, these new dematerialization options need to be "demonstrated" before China can be expected to adopt them as its own model for development. This puts the onus on countries in the developed world to investigate and pursue these alternatives.

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