China's Energy Transition

Pathways for Low Carbon Development

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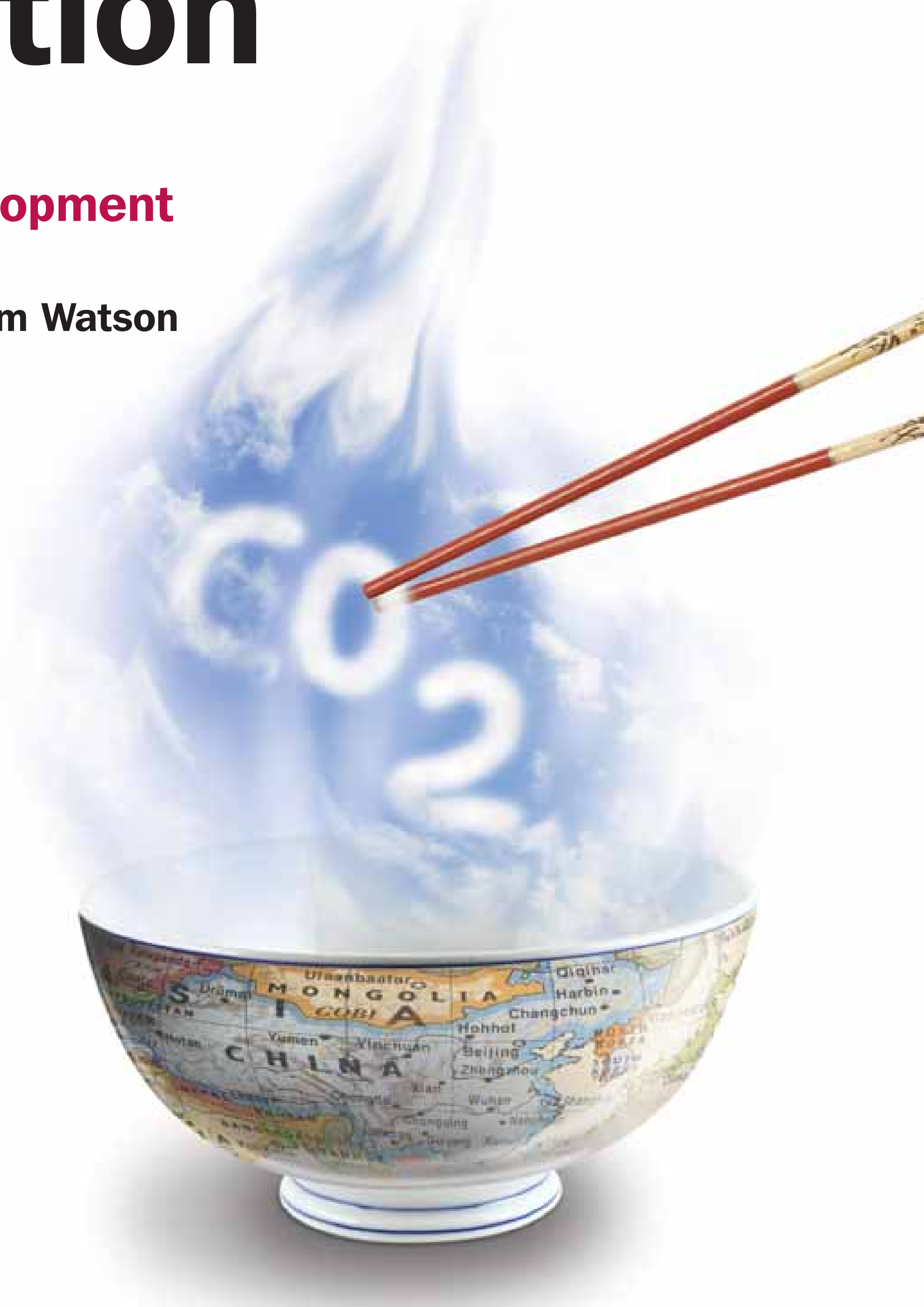

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Contents

1. Executive Summary

China's continuous economic growth over the last 30 years is a great achievement. This has significantly improved the living standards of more than 1 billion people. A major poverty eradication effort has resulted in 400 million people being lifted out of poverty between 1980 and 2000. GDP per capita has increased five times since 1981 (World Bank 2004). Alongside economic expansion, China has also experienced a large increase in energy demand despite a continuous decline in energy intensity between 1980 and 2000. As the Chinese economy moved into a new period of heavy industrialisation and urbanisation in the early 2000s, energy demand rocketed with a consequent increase in energy intensity between 2003 and 2005.

Due to this dramatic increase of energy demand, most of which is met by the use of coal, China became the world's largest carbon dioxide (CO_2) emitter in 2006. It is now widely accepted that a post-2012 international climate framework without the participation of China and the United States will be ineffective. However, such a framework must incorporate the development needs of China and other developing countries. In addition to leading to international calls for China to act to curb its emissions, China's recent energy demand growth has also led to concerns about energy supply, local and regional environmental pollution and social stability. This leads on to a fundamental question: can China's future development path be decoupled from carbon emissions growth? In other words, can China develop within the tight global carbon emissions constraints that climate science now says are necessary?

This report is the result of a three year research project funded by the Tyndall Centre for Climate Change Research, which explores the answers to this question. The project has investigated the potential trajectories of carbon emissions that China could follow to achieve a given climate change target – and how China might slow its emissions growth, and eventually enter a period of declining emissions. The report investigates in detail how these emission trajectories could be achieved through changes in China's economy and society, and the policies and technologies that shape China's energy system.

The target for China used in this report is a cumulative emission budget for China over the 21st century, which is derived from a global target of stabilising atmospheric concentration of CO_2 at 450 parts per million (ppm). According to the Intergovernmental Panel on Climate Change's (IPCC) latest assessment, achieving this target would mean that the world has a significant chance of avoiding some of the worst impacts of climate change. The report analyses four scenarios that are based on two different apportionment approaches for global emissions: namely equal emissions per capita and equal emissions intensity of GDP. The total global budget is 490 GtC (gigatonnes of carbon = 10^9 tonnes) over the 21st century. Within this, China is given a cumulative emission budget ranging between 70 GtC under the former approach, and 111 GtC under the latter. When combined with different medium term carbon emissions pathways, the implications of these budgets for China is a peak in emissions between 2020 and 2030, followed by a decline. Our research shows that early action to slow emissions growth and achieve a peak closer to 2020 is desirable because more of the carbon emissions budget is then available to smooth the subsequent emissions reduction pathway. The disadvantage of this is that China would need to implement far reaching changes to its economy and energy system sooner rather than later.

The four scenarios analysed in this report are distinctive from each other, but in general are divided by their relative positions on two critical issues: promoting innovation and the approach to social inequality. This report is not intended to be prescriptive about which of these budgets – or the many alternative pathways – China should follow. The scenarios analysed in the report are designed to illustrate some of the possibilities, and what the consequences of these might be for investment, economic structure and Chinese policy if they were followed in practice. Therefore, the report does not reach a firm conclusion on which scenario is the most desirable.

The scenario results show that the Chinese economy in 2050 will grow to between 8 and 13 times larger than today's size. The economy in all scenarios will be dominated by service sector, as is the case in most of today's industrialised countries. The structure of other industries varies between the scenarios. The total primary energy demand for 2050 also varies among scenarios, ranging from only 15% higher than 2005 to twice the 2005 level. As a result, the energy intensity of Chinese economy will be reduced by 76-87% between now to 2050, while carbon intensity has to be cut further to just 4-7% of the 2005 level. China's carbon emissions rise to between 24% and 72% higher than 2005 by 2020. But emissions subsequently decline to between 15% and 70% less than the 2005 level by 2050. Among all the sectors of the Chinese economy, transportation will have the highest growth within the scenarios. But energy consumption in households and industry hold the key to a successful transition to low carbon development in the next few decades. The full report describes in detail how this transition is achieved within each scenario.

This report highlights a number of key findings from the scenario analysis which are intended to inform policy making both within China, and in international negotiations. These key findings include:

1. Decoupling carbon emissions growth from economic development is challenging but achievable in China, and there is more than one way to achieve it. The four scenarios demonstrate different ways to square China's continuing development with a carbon emissions constraint. They reflect different priorities in governmental decision making, infrastructure investments and social preferences.
2. The four scenarios show that it is vital to start slowing emissions growth and to reach a carbon emissions peak as early as possible. The later the peak occurs, the more difficult it will be for China to comply with the emission budget. Furthermore, later peaks are often associated with steeper subsequent reductions in emissions which are likely to be much more challenging than shallower trajectories. Even in our scenario S4 which allocates nearly a quarter of the global budget of cumulative carbon emissions to China, a late emissions peak and high emissions trajectory between now and 2030 make it very difficult for China to remain within its budget. Our analysis clearly demonstrates that 2040 is too late for China's emissions to peak – and 2010 is inconceivable. A peak in Chinese emissions between 2020 and 2030 is therefore the most plausible way in which China could make a full contribution to global action to stabilise the climate.

3. The success and speed of economic and industrial structural change towards a more balanced service economy and high tech industries is likely to be key to China's low carbon development. Such a trajectory fits well with recent policy pronouncements of Chinese leaders, who are keen that China moves away from its recent energy intensive development path. In our scenario S2, where this change is successful and quick, economic growth is much faster and more sustainable and resilient to external shocks than in the scenario S4. S4 explores a pathway in which economic restructuring is less successful and slower, although energy demand and the emissions budget are roughly the same in both scenarios.
4. Energy efficiency is another vital factor for all four scenarios, although the challenges are different across scenarios. Currently the largest potential for energy efficiency improvement lies in China's industries. But the fast growing energy use in the household and transport sectors requires early action on efficiency if the overall energy efficiency targets in the scenarios are to be met. There is still time to head off pervasive carbon lock-in effects within these two sectors.
5. Renewable energy has huge potential to substitute fossil fuels in China, and to meet energy demand growth in the future. With proper policy support to enable innovation, development and rapid diffusion, renewable energy could contribute more than 40% of China's total energy demand in 2050, and more than 60% of power generation. By then, the amount of power generated by wind and solar PV could be larger than China's coal-fired and total power generation capacities today respectively. A large portfolio of renewable energy could significantly increase some dimensions of energy security such as the exposure of China to fossil fuel price volatility. Stability of the energy system with large contributions from renewables will be a serious issue, but could be managed by smarter grid technologies. The extensive deployment of electric vehicles in some scenarios could also help balance supply and demand.
6. In three out of the four scenarios, carbon capture and storage (CCS) plays a crucial role in helping China to develop within a carbon budget. CCS is not assumed to be implemented on a large scale in China until 2030, and will have to be employed quickly after that date if decarbonisation of the power system is to be achieved in these scenarios. By 2050, CCS will have to be installed to 80-90% of fossil fuelled power plants in scenarios S3 and S4. This means that action is required now, on an international basis, to assist China with the demonstration of CCS technologies. Only then will it be clear whether they will be technically and economically suitable for widespread commercial use.
7. Nuclear power can play a role in China's low carbon future. It does not have the crucial role that renewable energy technologies have within our scenarios. However, in the scenario with the most ambitious nuclear programme, China will build nuclear power plants three times faster than France has ever done. Within this scenario, the deployment of nuclear power reaches seven times the size of the current French nuclear power fleet in 2050. Yet even in this scenario, nuclear power only accounts for 30% of on-grid power generation and 12% of total energy demand. Concerns about nuclear security and fuel supply may be significant in limiting further deployment beyond this.

8. Achievement of a transition to a low carbon development pathway does not only depend on technology choices. As in other countries, social choices and the potential carbon lock-in in life styles and behaviour patterns will have significant impacts on future emissions. For a country like China that is building a large and influential new middle class, encouraging a green lifestyle and low carbon consumption behaviour could have strong exemplary effect on the wider population about the development pathways that are seen as desirable. This is an essential aspect of China's future story that should be addressed alongside measures for low carbon investment, institutional change and policy incentives.

While this scenario analysis focuses on China's potential future carbon emission trajectories, the economic and social transition within these scenarios has much wider implications than just carbon. This report therefore discusses its wider implications in the context of the availability of energy and other resources, some of the impacts on water and land resources, and the implications for China's energy security. It also shows that some of these implications are potentially serious if not thought through carefully. For example, the level of biofuels in China's transport sector envisaged in the scenarios could not be achieved using current first generation technologies. Second or third generation technologies would be required which potentially have much lower land use requirements and higher levels of sustainability.

Finally the report discusses the policy implications in China of the kinds of low carbon development pathways that are flow from this scenario analysis. All of the scenarios are ambitious and challenging, which would require comprehensive climate change and energy strategies to realise them in practice. This will have to build on the contemporary economic policy debate in China that is trying to rebalance the structure of Chinese economy. Through such strategies, China to build on the widely discussed "green opportunities" associated with the current economic crisis. Low carbon development is likely to mean more than the deployment of low carbon technologies and measures throughout China. It is also an opportunity for China to build on recent success stories in wind power and electric vehicles – and build low carbon industries and new institutions to foster low carbon innovation will be required to achieve this. International collaboration in technology and finance also have a crucial role to play, and are important parts of the post-2012 international framework. Within this framework, developed countries must make good on their repeated promises to assist developing countries like China with such technology and finance. Without such assistance, there is a greater risk that China will not move fast enough towards the low carbon development pathway that is necessary.

执行摘要

过去的三十年间中国经济的持续增长是一项伟大的成就，显著的改善十亿多人民的生活条件。在1980年到2000年间中国有四亿多人口摆脱了贫困，为消除贫困的全球发展目标做出了巨大贡献。与此同时人均GDP自1981年增加了五倍多（世界银行2004）。伴随着经济高速增长，尽管在1980年到2000年期间中国的能源强度持续下降，中国的能源需求仍然取得了大幅增长。随着2000年以来中国经济的重工业化以及城市化进程的深化，中国能源需求急剧增加，与此同时能源强度的持续下降趋势也在2003年到2005年间出现了逆转。

由于能源需求的大幅度增加以及煤炭在其中所占的巨大比重，自2006年起中国已成为世界上最大的二氧化碳排放国。一个没有中国和美国参与的后京都国际气候变化协议框架将不会取得任何实质效果已经是国际的广泛共识。但这样一个国际气候变化协议框架必须充分保障中国和其他发展中国家的发展权利。除了导致要求中国削减二氧化碳排放的国际呼声之外，中国近年能源需求的增长也导致了在能源供应，环境污染和社会稳定问题上日益加重的压力。这带出了一个根本的问题：中国的发展道路究竟能否摆脱碳排放的增加？换句话说，中国能否在当前气候科学认为所必需的严格的全球排放限制下实现发展？

作为英国廷德尔气候变化研究中心资助的一个三年研究项目的结果，这份报告对上述问题的答案进行了探索。这项情景分析研究探索了中国为实现特定气候变化目标可能采取的潜在的碳排放路径 – 以及中国如何减缓排放增加，并最终实现碳排放的下降。研究也详细分析了实现这种排放路径中国所需要的经济和社会变化，以及需要什么样的政策和技术来改变中国的能源体系。

报告中为中国设定的目标是一个中国在21世纪的累计碳排放预算，源自将二氧化碳浓度水平维持在450ppm的全球目标。根据政府间气候变化专门委员会最新的评估，这个目标意味着世界将有很大的可能避免最恶劣的气候变化影响。这份报告分析了基于两种不同的分配方法的四个情景，即相同的人均排放和相同的GDP能源强度.。全球在21世纪的累计碳排放总预算为4900亿吨碳，其中中国在21世纪的累计排放预算在第一种分配方法下为700亿吨碳，第二种方法下为1110亿吨碳。当与不同的碳排放中期路径相结合后，这些预算意味着中国需要在2020到2030年之间达到碳排放峰值，然后开始下降。我们的研究显示尽早开始减缓排放增加并在2020年前后到达峰值会更好，因为将留下更多的碳排放预算给剩下的时间以实现比较平缓的减排。但其不利条件在于中国将需要更快的在经济与能源体系中推进具有深远影响的改革。

报告分析的四个情景各自不同，但大致区别于它们在两个关键问题上的不同特征：鼓励创新与如何对待社会不平等。这项报告并不试图为中国选择特定的碳预算 – 或各种可能的发展道路选择。报告分析的情景是用来指出一些发展的可能，以及要将他们付诸现实会对投资，经济结构和中国的政策可能有的影响。因此，这项报告并没有决定哪个是更让人期待的情景。

情景分析的结果显示，到2050年中国的经济规模将是现在的8-13倍。在所有情景中经济都将以服务业为主导，与现在的发达国家类似。工业规模与结构在各个情景中有所不同。2050年的一次能源需求总量在各个情景中有较大区别，从比2005仅高15%到翻一倍不等。因此，中国经济的能源强度到2050年将比现在显著减少76-87%左右，而碳排放强度更是需要削减至只有2005年水平的4-7%。中国的碳排放到2020年将比2005年高24%到72%。但在碳排放随后将在2050年削减到比2005年低15%到70%。交通部门将是所有部门中能源需求增长最快的。而生活和工业部门的能源需求是中国在未来几十年内实现转型的关键。不同情景下实现转型的道路以及不同的未来勾画在报告中将有详细的阐述。

执行摘要总结了情景分析的一些主要成果以及由此对中国和国际决策者所提出的一些政策建议。主要结论有：

1. 在中国将经济发展与碳排放增长脱钩具有挑战性但也是可以实现的，并且有不止一种道路来实现。本研究的四个情景演示了在碳排放约束下实现中国持续发展的不同道路。但不同的选择体现了在政府决策，基础建设和社会偏好的不同优先度。

2. 四个情景都证明了尽可能早地进行减排和达到碳排放峰值至关重要。越晚遵守排放预算的难度就越大，而峰值之后所中国必需的减排也越急剧。并且，较晚的峰值通常伴随着更陡峭的减排曲线，因而比较平缓的减排更难以实现。即使如情景S4中中国拥有将近全球累计碳排放四分之一的预算，较晚的排放峰值和到2030年前的高排放轨迹使遵守碳预算成为了一项艰巨的任务。我们的分析清楚的显示了2040年达到排放峰值将太晚 – 2010年又不太现实。因此中国的碳排放在2020年至2030年间达到峰值并随后下降将是中国全力支持稳定气候的全球行动的最现实的贡献。

3. 中国的低碳发展关键在于经济与产业结构迅速而成功地实现向更加均衡的服务经济和高科技高附加值产业的转变。中国决策者希望能让中国摆脱最近的能源密集型的发展道路，因此这种转变也符合他们最近宣布的一系列政策。在情景S2中这种转变比在情景S4中更成功而且更迅速，经济增长也更快、更可持续和更抗风险。而情景四则描述了一个这种转变相对不成功且缓慢的经济，尽管其能源需求与碳预算与情景S2一样。

4. 能源效率是另一个在所有四个情景中都重要的因素，尽管情景之间的具体挑战有所不同。虽然目前最显著的能效提高潜力在工业部门，但要实现情景中的能效水平，则需要尽早注重对正高快速发展的生活和交通部门的能效提高。我们现在还来得及来预防这两个部门中可能会广泛出现的碳锁定效应。

5. 可再生能源在替代化石能源和满足未来能源需求增长方面拥有巨大的潜力。如果能有合适的政策支持以实现可再生能源的快速发展和大规模应用，可再生能源可以满足中国2050年总能源需求的40%及电力需求的60%以上。届时，中国的风力和太阳能发电装机容量将分别超过现在中

国火力发电装机量和总发电装机量。大规模的可再生能源组合将显著的增强能源安全，如化石燃料价格的大幅波动。包括大量可再生能源的能源系统的稳定性是一个严重的问题，但可以通过更智能的电网来管理。数量庞大的电动汽车在一些情景中也可以用来帮助调节电力供需平衡。

6. 碳捕捉与储存技术（CCS）在所有四个情景的三个中都对该情景遵守碳预算起到了不同程度的重要作用。我们假设CCS在2030年以后才开始在中国得到大规模的应用，并在某些情景中快速的应用以实现电力系统的去碳化。到2050年，CCS在情景S3和S4中将必须被应用到80-90%的火力发电装机中。这意味着中国的CCS示范项目必须得到国际范围内的帮助。

7. 核能将在中国的低碳未来中将占有一席之地，但在我们的情景中不及可再生能源那样至关重要。但是在一个拥有宏伟的核电发展计划的情景中，中国将以法国核电历史上最快速度的三倍修建核电站。在这个情景中，中国的核电装机将在2050年达到法国现在核电装机总量的7倍。即便如此，核电也只能贡献上网发电量的30%和总能源需求的12%。关于核电安全和核燃料供应的将会限制其进一步的发展。

8. 实现向低碳发展的转型并不只是技术上的选择。和其他国家一样，社会选择和生活方式与行为模式上潜在的碳锁定效应将对未来的低碳发展道路产生显著的影响。对于中国这样一个正在形成庞大且有影响力的新兴中产阶级的国家，鼓励绿色的生活方式和低碳的消费行为将对更多在沿着这条发展道路前行的人们起到很好的榜样作用。这是中国未来非常重要的一个方面，需要与低碳投资，制度改革和政策激励一起受到关注。

尽管这个情景分析的重点在于中国将来的碳排放路径，这些情景中的经济与社会转型的影响却远远不止于碳排放。这份报告的后部分从能源和其他资源的可利用性，对水和土地资源的影响，以及对能源安全的影响等方面讨论了这些转型的影响。报告指出了如果没有仔细考虑，有些影响将可能非常严重影响。比如，中国交通领域的生物燃料需求将不可能通过现有的第一代技术实现。这将需要对土地要求小得多并更可持续的第二代或第三代生物燃料才能实现。

最后，报告讨论了该情景分析所描绘的中国低碳发展之路的政策涵义。所有的四个低碳发展情景都是很有挑战性的宏伟蓝图，因而需要全面的气候变化和能源战略来实现。这些战略也必须将中国正在进行的关于重新平衡经济发展结构的政策讨论纳入其中。通过这样的战略，中国将能够抓住现在经济危机下广泛讨论的“绿色机遇”。低碳发展不止是应用低碳技术与措施。这也是中国在最近比较成功的风电和电动汽车案例上认识到的一个机遇 – 建立低碳产业与新制度来促进所需要的低碳创新。国际间技术与资金的合作也将扮演重要的角色，同时也是后京都国际气候变化框架协议的重要内容。在这个框架协议下，发达国家必须履行他们一再承诺过的对像中国这样的发展中国家的技术与资金支持。没有这些支持，中国将很可能难以像她所需要的那样迅速的实现向低碳发展道路转型。

2. Introduction

China's economy is growing rapidly with nearly 10% GDP growth per year over the last two decades. At the same time, economic expansion is leading to large increases in energy demand despite a continuous decline in energy intensity between 1980 and 2000. Since 2000, quick expansion of heavy industries such as iron and steel has led to accelerating energy demand growth and a trend of increasing energy intensity between 2003 and 2005. Coal continues to dominate China's energy system despite a slowly declining share, and is fuelling the majority of power generation. China's generation capacity reached nearly 800 GW in 2008, of which three quarters was coal fired. Imported oil is also increasing sharply to over 50% of total oil consumption – up from 29% in 2000 as domestic output has matured. Demand for natural gas keeps growing, and largely exceeds the supply capacity.

These trends lead to a number of pressing challenges. Securing enough energy to sustain economic growth is an important priority for the Chinese government. Alongside this, more attention is being given to addressing the environmental effects of economic development and energy consumption. These include severe desertification, air and water pollution in China and an increasing contribution to international environmental problems like climate change. China is now the world's largest emitter of carbon dioxide (CO_2), the most important greenhouse gas (GHG)[1] , after a 50% increase between 2000 and 2005. At the same time, China is particularly vulnerable to the impacts of climate change. Aware of the huge challenges ahead, the Chinese government has implemented various measures and targets to reduce China's reliance on fossil fuels, particularly coal and to mitigate the impacts of rapid economic growth. But effects of these measures are yet to be seen, and they are at best only starters of what are needed to address China's environmental concerns and the implications for the international challenge of tackling climate change.

Against this background, this report sets out the results of a three year research project conducted by the Tyndall Centre for Climate Change Research. The project aim was to assess alternative energy futures for China, and to evaluate the scope for mitigating CO_2 emissions while achieving development targets. A key question for the research is whether China can avoid the problem of 'carbon lock-in' that is faced by most developed countries. This is characterised by dependence on carbon intensive energy systems, infrastructure and social economic structures that are difficult to change. The project has explored a range of scenarios for China's future energy trends and carbon emissions to inform policy making in both China and the UK.

The next section of the report (section 3) provides some background on China's energy system, its recent development and the current policy landscape. Sections 4 and 5 set out four cumulative carbon emission scenarios for China over the 21st century that achieve economic development within the constraints of a global emission budget. This budget is designed to stabilise carbon dioxide concentrations at 450 parts per million (ppm). If achieved, there is a significant probability that the most severe impacts of climate change will be avoided. A key assumption is that other countries pursue equivalent actions that are also commensurate with the same stabilisation target. These sections also include a detailed analysis of the different energy and social-economic implications of these pathways for China's future development. Section 6 then moves on to

[1] EIA (2008), available at http://www.eia.doe.gov/pub/international/iealf/tableh1co2.xls

analyses some of the possible consequences of the scenarios for energy resource use and energy security. Finally, Section 7 provides some pointers for policy makers which stem from the scenario analysis.

This report is not intended to be prescriptive about the pathway that China should follow over the coming decades. Instead, it explores a variety of alternative development futures that China could choose, each of which is constrained by an overall cumulative emissions budget. By doing so, the report is designed to provide policy relevant insights into the kinds of changes in the Chinese economy and energy system that might be required if development is to continue within a carbon emissions constraint.

3.China's Energy Trajectory

China's Energy and Environmental Challenges

China's rapid industrial growth over the past twenty five years has led to a rapid increase in energy demand. The International Energy Agency (IEA) estimates that China and India alone are expecting to contribute 51% of the incremental world primary energy demand in the period to 2030, despite a global economic slowdown in 2008 (IEA 2008a). With an over 55% increase in primary energy demand between 2000 and 2005, China now accounts for more than 16% of global primary energy demand and will overtake the US as the world largest energy consumer soon after 2010 (IEA 2007a). China's enormous energy demand partly stems from a rising standard of living of the world's largest population, rapid growth in the world third largest economy, deepening industrialisation and urbanisation over the last ten years, and an increasing influence on the world trade system. Yet, China's energy demand is not increasing in the most efficient way. Most of the incremental energy demand is met by increased production of domestic coal, with severe environment and health impacts in each step along the chain from extraction to consumption. The large expansion of coal use is partly due to the pursuit of energy self-sufficiency as China has abundant coal reserves. It is also because coal is the cheapest energy source for China when the enormous external costs are not accounted for. Figure 1 indicates the close trend between domestic energy production and total energy demand in China since 1980. The fast growth of coal consumption is believed to be one of the main reasons for China missing the environmental targets in its 10th Five-Year Plan between 2000 and 2005. There has been a remarkable unswing in sulphur dioxide (SO_2) emissions, over 90% of which is from coal combustion. Energy-wise, China's declining energy intensity over the last two decades was

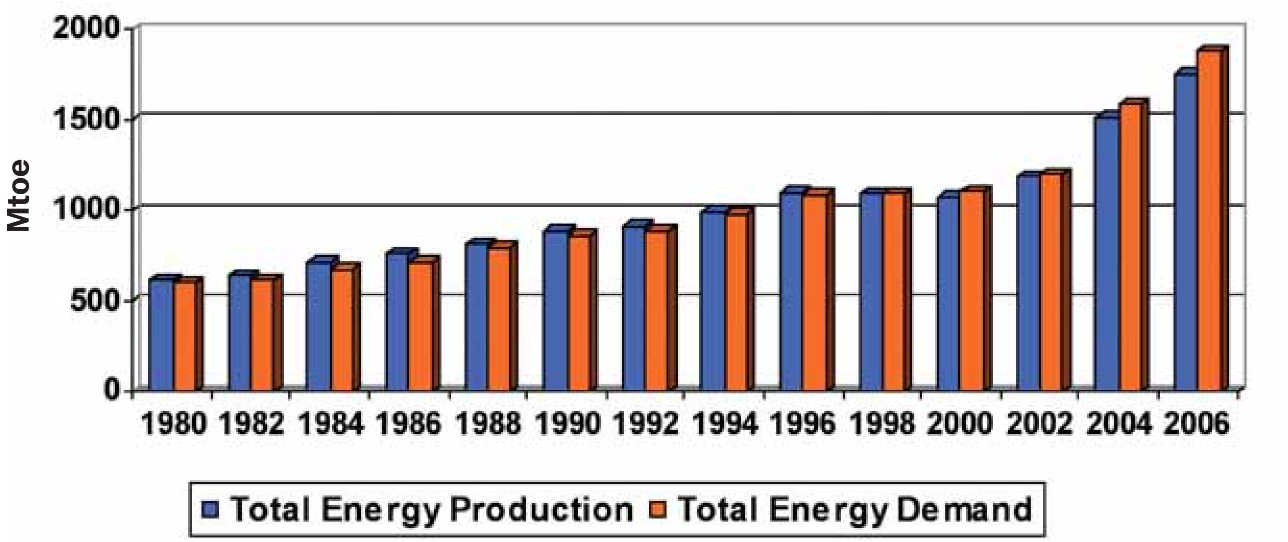


Figure 1: Growth in China's primary Energy Production and Consumption

also reversed for the first time in 2004 and 2005, and so was the declining share of coal in China's energy mix. To meet this soaring energy demand, China's power sector has undergone an unprecedented expansion, whose generation capacity increased two and half fold from 319 GW in 2000 to 793 GW in 2008. Although most of the increase is through coal fired power plants, the rate of increase is as fast for hydro power, and much faster for nuclear and wind power. Oil demand increased sharply in both industry and transport sectors, much of which has to be met through imported oil as domestic production matures. Imported oil accounts for 52% of total oil consumption in 2008, a huge leap from only 29% in 2000. Consumption of the cleanest fossil fuel, natural gas, tripled from 24.5 billion cubic meters (bcm) in 2000 to 72 bcm in 2008 (Ren 2009), and will continue to rise as the construction of pipelines progresses.

The development road China has taken and is still taking is unsustainable and has induced severe environmental problems. Energy and water shortages, water and air pollution, cropland and biodiversity losses are all escalating as economic growth continues. Having fuelled the previous miracle economic growth, China's coal based and inefficient energy system has led to a number of challenges which have the potential to work against China's future economic growth. Sulphur dioxide caused by the coal combustion is now resulting acid rain falling on more than 30% of China's total land, ruining croplands and threatening food chains and water systems. 16 Chinese cities are ranked among the most polluted 20, mostly due to the production and use of coal. The World Bank estimates around 400,000 people in China die each year from air pollution-related illnesses, mainly lung and heart diseases (McGregor 2007).

The environmental impacts of China's economic growth can also be felt beyond the border of China. Alleged as the world largest emitter of CO_2 since 2006 (EIA 2008), China's carbon emissions increased by over 50% between 2000 and 2005. It is not surprising that there is renewed call for China to take more responsibility for mitigation in the post-2012 international climate agreement which is currently being negotiated. Although China is now the global top emitter of CO_2, it has only accounted for 7% of cumulative emissions between 1850 and 2000, far behind US and EU which is responsible for almost 30% of cumulative emissions each (Pew Center 2008). China's CO_2 emissions per capita was just over 4 tonnes in 2006, and is much less in cumulative terms. Although it is still only one fifth of the US and about half of the EU, it is almost four times of India, another emerging economy that is usually shares the pressure to reduce CO_2 emissions with China. Large increases in energy demand has not only led to international pressure on China to act on environmental issues, it has also led to worries about securing energy supplies and a hefty cost due to volatile energy prices in the last two years. To conserve energy and reduce the exposure to energy security risks (and carbon emissions growth), Beijing has already committed to a 20% cut in China's energy intensity in the 11th Five-Year Plan by 2010 (National People's Congress 2006).

What is less heard of than China's ever rising carbon emissions is that China itself is one of the most vulnerable countries to the adverse consequences of climate change. This has been emphasised as a real concern to the Chinese government in the first National Assessment Report on Climate Change (MOST, CMA et al. 2007) and China's National Climate Change

Programme (NDRC 2007a). With only one third of the world's average land availability per capita and 27% of the world's average water resources per capita, the availability of cropland and water resources will be pressing concerns for China's sustainable agricultural development. This will cause up to a 40% reduction in cereal production if proper adaptation is not taken (Xiong, Conway et al. 2009). The total area of China's western glaciers will shrink by over 27%, threatening long term water supply to several of the most populated river basins in the world. The current imbalance of water distribution will be exacerbated. Droughts, floods, typhoons and other extreme weather events will cause tremendous economic losses and harm China's fragile environmental system.

For the reasons above, it is unsurprising that the Chinese government are taking climate change more seriously than seen before, with an obvious attitude change seen in the latest international conferences of the United Nations Framework Convention on Climate Change (UNFCCC) in Bali and Poznan. At the top leadership level, combating climate change and adapting to its adverse impacts was incorporated into Chinese President Hu Jingtao's report delivered in October 2007 at the 17th National Congress of the Communist Party of China and Premier Wen Jiabao heads the National Climate Change Response Leading Group that includes 29 top ministerial officials from all 28 ministerial agencies. In line with the top level demand, various measures and policies have been taken in China to address the energy and climate issue from both supply and demand side, and to pave the way towards sustainable development in the coming decades. It would be imprudent to believe that China is now fully devoted to tackling climate change as most of these policy changes are primarily driven by concerns about local and regional environmental pollution and energy security. But co-benefits of these policies are in line with China's principle "to address the climate change within the framework of sustainable development" (NDRC 2007a). This is an important way to increase the participation of developing countries to a post-2012 international climate agreement.

Rocketing Demand

The primary energy consumption in China has grown almost four fold since 1980 to nearly 2500 million tonnes of coal equivalent (Mtce), most of which is driven by a huge expansion of industry, particularly the quick growth of heavy industry since 2000. As China embarked on its latest phase of heavy industrialisation and faster urbanisation, energy demand rocketed in the early 2000s. As people's living standards have risen with economic growth, China's energy demand is set to keep growing in the next decade or two. Contributions to growth from the household and transport sectors will be significant despite a large potential for energy efficiency improvement. Industry accounts for a large proportion of China's energy demand: around 70% of end-use energy consumption in 2002 (Dai, Zhu et al. 2004; LBNL 2004). However the mix of energy consumed by industry has changed dramatically with the proportion of coal falling from 45.4% in 1985 to 22.0% in 2002, while electricity has risen from 25.8 to 43.6% at the same time. Due to its crucial contribution to China's energy demand, the Chinese government started the "1000 enterprises programme" as a key step to improve energy efficiency in the vast industrial sector. These 1000 industries are all huge companies which account for nearly half of total industrial energy consumption and a third of national total (NDRC 2007b). This programme aims to reduce 100 Mtce from baseline annual energy demand by 2010 through energy efficiency improvement. This is equivalent to 260 million tonnes (Mt) of CO_2.

Structural change in energy consumption is also seen in the household sector where coal's share of residential energy consumption dropped from over 90% to 30% in by 2002. In the same period, there was an almost a 20 and 25 fold increase in residential consumption of electricity and natural gas. In most areas, quick penetration of household electric appliances is the driver behind the increased consumption of electricity, such as TVs, washing machines, refrigerators and air conditioners (Zhang 2004). Electricity consumption of a large number of air-conditioners in the rich east coast cities has been accused of causing power shortages in summers. To the north, old and inefficient coal fired district heating systems charge consumers at a fixed rate with no individual control, discouraging any energy saving efforts. They are responsible for the poor air quality in northern China in winter. However, the average residential energy consumption in China is still well below the level of developed countries and huge growth is expected with growing income. China has put in place stringent energy efficiency requirements in the latest building code and established energy efficiency labelling for electric appliances. However, their implementation is still open to question.

Energy consumption in transportation has increased 4.5 times in 25 years since 1980. Most of growth has been driven by a seven fold increase in energy consumed by road vehicles (IEA 2008b). This has been markedly represented by a 37% annual growth in private vehicle sales between 2000 and 2006. China is now the second largest automobile market after US and the third largest automobile manufacturer and is expected to take the first place in both in around 2015. But this is only part of the picture. Both aviation and shipping are growing at much faster speed. Passenger- and freight- distance by air has increased by more than 50 times in 25 years since 1980, and 10 times for freight-distance in shipping. China has started to address energy consumption in the transport sector and its consequent pollution, particularly from the booming road transport sector. The Chinese government has an ambitious plan to narrow the gap with leading nations, like those of the EU, in fuel economy and emission standards for its growing passenger vehicle fleet. This is supported by recently revised consumption taxes in favour of energy efficient small engines and alternative fuel vehicles such as hybrid or all-electric cars. China's fuel economy standards for vehicles are catching up with those of Japan and the EU. They are already more ambitious than those of US and Australia. In July 2007 China implemented State III (similar to Euro III) vehicle emission standards and is scheduled to move to State IV (similar to Euro IV) in July 2010. Beijing has already implemented State IV in July 2008.

Coal-dominated Supply

China has the third largest coal reserve after US and Russia, but has been the world's largest producer and consumer of coal since 1990s (Andrews-Speed 2004). Despite a significant shut-down in late 1990s, the proliferation of small township and village coal mines in China still accounted for more than 50% of China's annual production of coal in 2000 (Gao, Qu et al. 2004). This dropped to less than 40% in 2007 after further efforts to integrate and upgrade capacity of the coal industry. China produced 2.7 billion tonnes of coal in 2008 compared with around 1 billion tonnes in 2000. Coal will maintain a dominant position in

China's energy supply for the near future, although it is likely to be more and more costly to use in the future.

China has small reserves of oil and gas - roughly 1/15 of world average per capita. With only 1.3% of world proved oil reserves (BP 2008), China is now the world's fifth largest oil producer and second largest oil consumer. It is no surprise that IEA estimates China's oil import dependency rise to over 80% by 2030 as the gap keeps growing between demand and domestic production (IEA 2007a). Demand for natural gas is the smallest in fossil fuels, yet has the fastest growth. It is estimated that demand for natural gas will jump to 200 bcm in 2020, nearly a nine fold increase from 2000. Most of China's natural gas reserves are located in remote areas, making them difficult to access. This requires large investment in delivery infrastructure like the 3900 km-long East-West pipeline. Half of the natural gas demand will be met through imports by extending pipelines to Central Asia and liquefied natural gas (LNG) terminals in the east coast.

Over 80% of China's power generation is fossil fuelled, almost entirely from coal, as indicated by Figure 2. The power sector accounts for almost half of China's coal consumption. Many power plants are small and old that are among the dirtiest in the world. To upgrade the fleet, China plans to close down 50 GW of inefficient and small generation capacity between 2006 and 2010 whilst restricting new additions to large state of art supercritical and ultra-supercritical units. In 2008, 17 GW of inefficient capacity has been closed down. The overall efficiency of coal fired power plants has improved from 370g of coal per kWh of electricity (g coal/KWh) in 2005 (Zhang and Zhao 2006) to 349g coal/KWh in 2008, exceeding the 11th Five-Year target of 355g coal/KWh by 2010 2 years early.

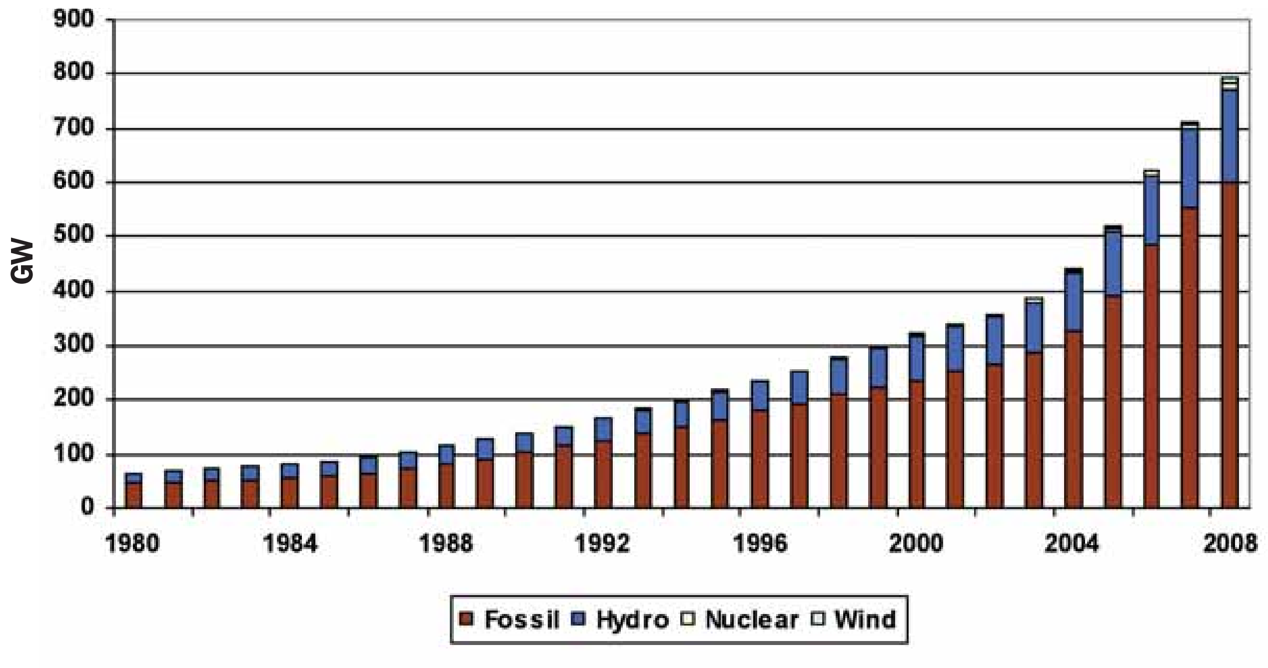


Figure 2: China's power generation mix

But China also has the world largest hydro power generation capacity, twice the size of the second largest in Canada. It is symbolised by the 22.5 GW Three Gorges Dam, of which 18.2 GW have already been brought to commercial operation since October 2008. Apart from large hydro, China also had over 60% of the world's small hydro power generation capacity in 2006 (REN21 2008). The Chinese government plans to further increase hydro power generation capacity from 172 GW to 300 GW by 2020, mostly from large hydro.

China installed the first nuclear power plant in 1993 but no new capacity was installed until 2002. As China has revised its nuclear power strategy much quicker development of nuclear power is expected. The capacity increased from 2.1 GW in 2001 to 10.8 GW in 2008, with 11 GW under construction and a further 15 GW approved (WNA 2009). The Chinese government made plans in 2006 to have 40 GW of nuclear power by 2020 but is now considering raising this to 60 GW

Wind power is currently enjoying the fastest growth in all power generation technologies, almost doubling the installed capacity every year since 2004. As a result, it has grown from 0.76 GW in 2004 to 13.24 GW in 2008, on track to beat the government's 30 GW by 2020 wind power target by 200% (The Climate Group 2008). China now has the world's fourth largest wind power capacity after US, Spain and Germany. Some believe China could reach 100-120 GW by 2020 and up to 270 GW in 2030 (Li, Gao et al. 2008). Figure 3 shows the recent take off of China's wind power. Although solar photovoltaic (PV) is still rare in China, the Chinese solar manufacturing industry is second only to Japan with more than 400 solar companies including the world's 4th largest PV producer, Suntech. This makes it possible to upscale quickly in China when the cost of solar PV declines further. On the other hand, solar water heaters are now installed in 10% of Chinese households, accounting for nearly two-thirds of total global capacity and three quarters of the annual addition of solar water heaters (REN21 2008).

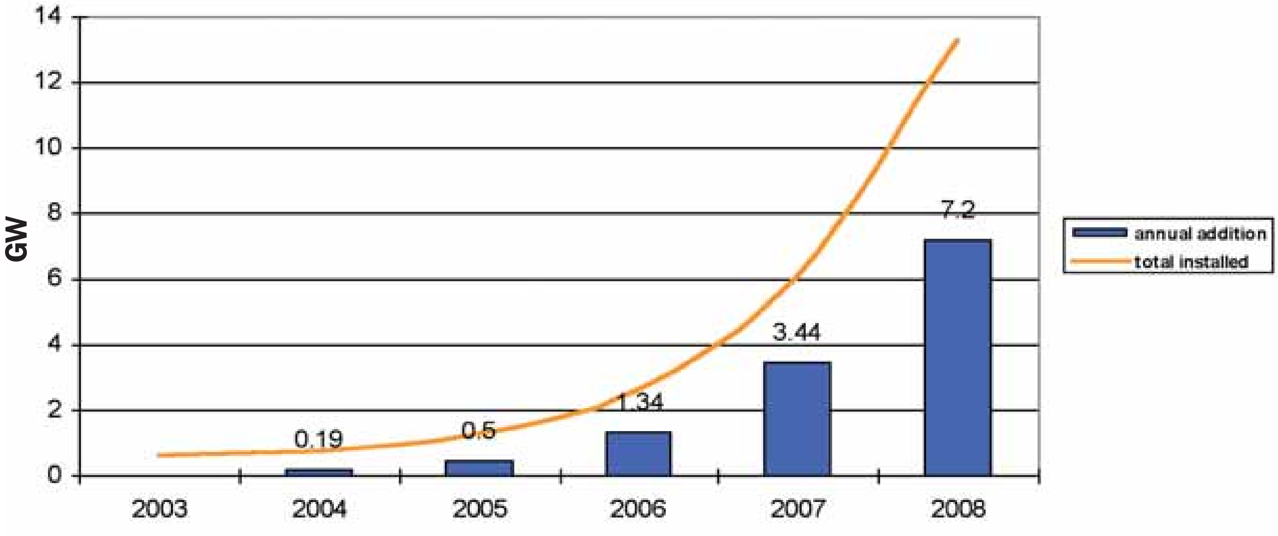


Figure 3: China's wind power growth 2004 – 2008

Policy Responses

The overall goal of Chinese energy policy is to achieve a sufficient energy supply to enable sustained economic growth. One of the strongest energy policy drivers in the last few years has been the government's attempt to gradually liberalise the energy sector to remove the inefficiencies of central planning and secure energy supply for the future. Diversification of energy supply, energy efficiency improvement and energy-environmental concerns are also rising up the government's agenda. Energy policy in China has evolved a lot in the last two decades, but many experts point out that it is still lagging behind the development of energy system itself, in many cases only passively responding to the change rather than proactively shaping the future (Gao, Qu et al. 2004; Sinton, Stern et al. 2005).

China achieved an unprecedented continuous energy intensity reduction between 1980 and 2000. While its GDP grew more than four fold, energy demand only doubled at the same time. The Chinese government has set up the same target for itself for the next 20 years, declared as a national development goal in the 16th National Congress of Chinese Communist Party (CCP) in 2004: to quadruple the economy with only a doubling of energy demand between 2000 and 2020. China is also putting more effort into liberalising the pricing mechanism of energy and reforming the energy market. These efforts, however, have only been implemented in some sectors. The lack of a more comprehensive systematic reform of pricing is causing serious price distortion in some cases.

As the Chinese Premier Wen Jiabao urged China to build a resource-saving, environmentally-friendly, thrifty society[2], energy efficiency is now announced as the first priority of China's energy policy in the 11th Five-Year plan (National People's Congress 2006). The government is taking a lead in promoting energy efficient products through large scale government purchasing. The Ministry of Finance (MOF) and the NDRC issued government procurement regulations for energy efficient products in December 2004, requiring local and national governments to purchase energy efficient products for replacement (CESP 2005). Given the vast size of inefficient industry and potential growth in household and transportation, progress made in energy efficiency will have a large effect on China's energy future.

What is also important in abating China's fast growing energy demand as well as carbon emissions is to rebalance the structure of economy and industry. This means shifting away from the expansion of energy and resource intensive industries, and away from too much reliance on export-led growth. By increasing domestic demand's contribution to economic growth and developing more high tech and high value-added industries to enable a higher position in the global production value chain for the Chinese industries, the economic growth in the future will also be more resilient to external shocks and more sustainable in itself. As Lardy (2007) has pointed out, China's recent growth has been driven by a large, growing trade surplus and rising investment in energy-intensive sectors such as coal, steel, cement and chemicals. This partially led to China's disproportionate growth in energy demand and emissions in the early 2000s.

Despite becoming a major global trade power, 60% of China's exports in 2006 were from multinational ventures in China[3]. These ventures account for the majority of high-tech and high value-added exports from China (see Figure 4). Overall, China's exports are still dominated by low technology products or the low value part of

[2] Speech in his Government Work Report delivered in March 2006 at the annual legislative session of the National People's Congress

[3] 26th August 2007, Mr.Bo Xilai, Minister of Commerce of China, speech on the ASEAN Economic Ministers meeting.

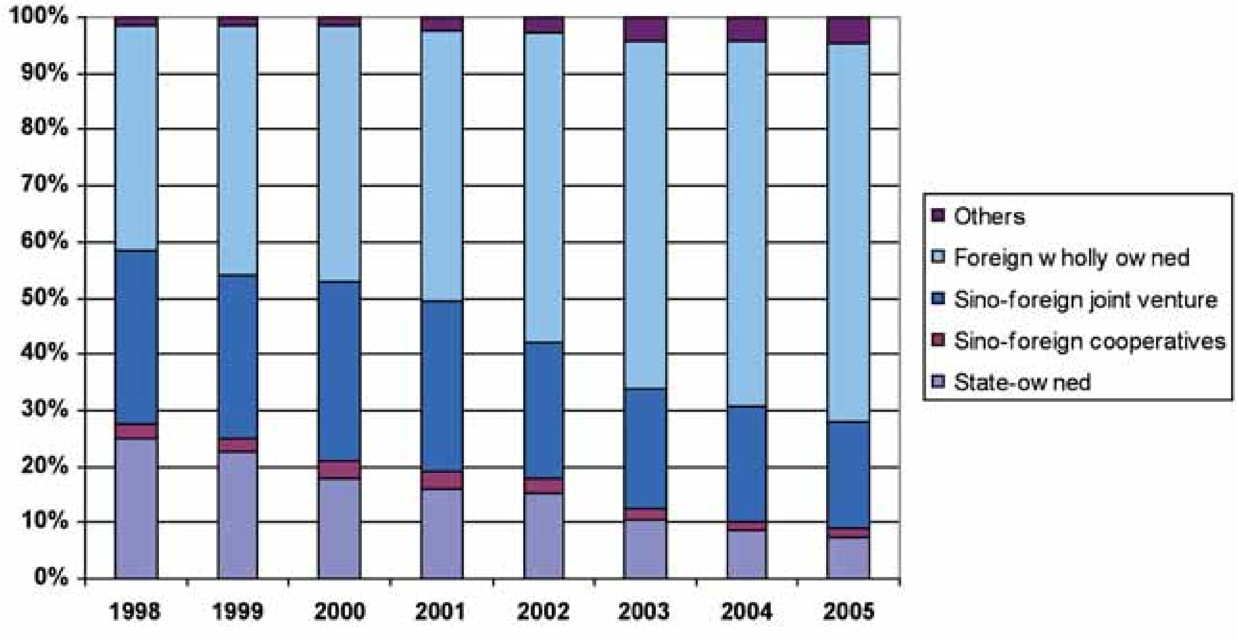


Figure 4: Chinese high-tech exports by ownership of firms Source: OECD (2008)

medium-high technology products. Imports are mainly high value added medium and high technology products (Sachwald 2007), which is almost the opposite to most of the technology-based economies like the UK, US, or Korea. This acutely reflects the relatively low position of the Chinese economy in the globalised market and production value chain. There has been a clear recognition within the Chinese government that without structural change of the economy, neither its short-term 20% energy intensity reduction target nor the medium-term target of quadrupling economy with double energy demand by 2020 could be achieved (Andrews-Speed 2009). Having been clearly emphasised this message in the 11th Five-Year plan, it has been reinforced by the Chinese government's recent economic stimulus package responding to the global economic slowdown. Whilst the Chinese government is trying to rebalance the pattern of growth so that services, higher value added industries and domestic consumption act as more important drivers in the future economy, the impact of these policies is yet to be seen.

There are also marked changes in China's energy strategy. It is notable that the famous phrase, "mainly based on coal", despite its existence in the 11th Five Year-Plan, is quietly removed from the proposed China's future energy strategy in the 2007 China's Energy White Book (State Council 2007). At the same time, the Renewable Energy Development and Utilization Promotion Law (Renewables Law), which came into effect in 2006, saw the government's ambitious renewable energy development plan for 2020 outdated in less than 2 years due to the renewables boom. The Chinese government aims to raise renewable energy's share in China's primary energy demand to from 8% in 2006 to 15% in 2020. This is reinforced by targets for 300 GW of hydro power, 30 GW of wind power and biomass, 40 GW of nuclear power and a modest target for solar energy (NDRC 2007c).). Many of these targets seem likely to be overtaken by rapid progress with implementation. Other Chinese energy policy priorities include diversifying the current energy mix, reducing dependency on fossil fuels, particularly those that are imported, mitigating environmental pollution, and safety issues in energy production and consumption. But all these ambitions will remain as ambitions unless institutional changes continue, market reform continues to progress, and regulatory revisions are pursued. The seriously short-staffed energy and environment administrations in the Chinese government will need more resources and a coherent vision that is shared with powerful economic departments.

4. Future carbon emissions budgets and trajectories for China

Scenarios are now widely used to investigate potential future developments but they are neither predictions nor forecasts (IPCC 2000). Scenarios are often used for the assessment of future developments that are either inherently unpredictable or highly uncertain. This usually means that a coherent set of scenarios is developed to explore the key dimensions of these uncertainties. Within this, each scenario describes and analyses just one possible future.

A large number of scenarios have been developed in recent years that are designed to explore future emissions in greenhouse gases, their potential impacts and abatement strategies. One of the most notable scenario exercises that focus on climate change is the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) published in 2000 (IPCC 2000). This includes four different narrative storylines that represent different demographic, social, economic, and technological driving forces. Their environmental impacts are further developed to examine the range of outcomes for greenhouse gas emissions (IPCC 2000). 40 SRES scenarios have been categorized in four large scenario families (known as A1, A2, B1 and B2). Many of the climate change and energy scenarios developed ever since then are more or less based on this scenario families.

There are a number of appraches to scenario building. The ‘forecasting approach’ where scenario exercises start with the present and use simulation techniques, modelling or other forms of projection to develop a set of potential future trajectories or ‘storylines’, and the ‘backcasting approach’ where scenarios start from a desirable future state using backcasting techniques to develop their storylines. This is used to understand the range of developments and changes could occur to achieve the desired future state.

There is also a distinction between ‘top-down approach’ which starts with an overview of the system and overarching principles, and then move to specific details and ‘bottom-up approach’ which aggregate specific details at the micro level to build up the picture of overall trends. The choice of a top-down or bottom-up approach depends on the requirements of a particular scenario set.

A number of scenario exercises have explored potential long-term trends in energy and CO_2 emissions in China and the UK. Three of these which are particularly relevant to this report are summarised below.

The first is the scenario analysis of China's energy demand to 2020 by the Chinese Energy Research Institute (ERI) in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in the US using the LEAP 2000 model (hereafter ERI 2020). The scenarios differ mainly in the extent to which sustainable development policies are implemented, the energy market is liberalised and China adapts to WTO membership and globalisation (Dai, Zhu et al. 2004). This scenario analysis only evaluated some relatively modest possibilities for change, and it soon proved to be outdated after China’s energy demand surged from 2003.

The second is a set of long term emission scenarios to 2050 developed by ERI using an Integrated Policy Assessment model for China (IPAC) (hereafter ERI 2050). Directly focusing on carbon emissions, the scenarios did not incorporate any international emissions or climate targets. The superior Policy and Technology (P&T) scenario leads to a 40% reduction in CO_2 emissions compared with the Business as Usual (BAU) scenario. Although the emissions reduction falls short of people’s expectations today, it provides an indication of China’s large emission reduction potential.

The third set of scenarios were developed in the Tyndall Centre's projects *Decarbonising the UK* (Anderson, Mander et al. 2008) and the subsequent *Living Within a Carbon Budget* (Bows, Mander et al. 2006). A cumulative emissions approach is adopted in the latter to give a cumulative CO_2 emissions budget for the UK. The scenarios are consistent with stabilising the global atmospheric CO_2 concentration at 450ppm, with different assumptions for energy supply, energy demand, efficiency improvement and sectoral changes. One of the most important features is the two distinguished approaches to reduce carbon emissions, either by reducing energy intensity of the economy, or by reducing carbon intensity of energy supplies.

Our carbon emission scenarios for China use backcasting combined with a chosen cumulative emissions budget. This is similar to the method used for *Living within a Carbon Budget.* The following section will first discuss how the cumulative emissions budget has been developed for China for the 21st Century, and show how a range of possible emissions pathways were developed from now to 2100. These certainly do not describe all possibilities – but are designed to help explore some key dimensions that have been identified in two stakeholder workshop discussions that were held in Beijing and London. Each pathway has an associated storyline that describes changes in the economy, technology, governance and society. These changes affect the energy consumption and carbon emissions of different sectors such as households, transport, power generation and industry. It is important to note that we have adhered to the principle of making no judgement of the most desirable or likely scenario in generating these storylines. However, there are clear policy implications of these scenarios (see Section 7 of this report) which tend to favour some scenarios over others.

Choosing a global budget

As CO_2 stays in the atmosphere for more than 100 years, emissions from many decades ago will have a similar impact on the climate as today's emissions. Therefore it is reasonable to investigate the possibility of *limiting cumulative emissions* of CO_2 over time rather than simply analysing specific percentage cuts in emissions by specific dates (Anderson, Bows et al. 2008). As noted earlier, this approach has already been used by the Tyndall Centre in its most recent scenarios for the UK (Bows, Mander et al. 2006).

Following on from this, our project analyses China's cumulative emissions of CO_2 over the 21st century. We chose a cumulative emissions budget for China that is commensurate with a target for the stabilisation of CO_2 concentrations in the IPPC Fourth Assessment Report (AR4) Working Group 1 report (IPCC 2007a). This states that global cumulative emissions for this century should be no more than **490 GtC** (gigatonnes of carbon = 10^9 tonnes) in order to stabilise the CO_2 concentration at 450 ppm. Given the assumptions for other greenhouse gases in the IPCC report, this is roughly equivalent to a concentration for all greenhouse gases of around 550 ppm CO_2 equivalent (CO_2e) (IPCC 2007b). According to the report, this is likely to result in a global average temperature rise in the range 1.9-4.4°C above pre-industrial levels, with a mean of 2.9°C (IPCC 2007a). This stabilisation level is almost the upper level that is recommended in the Stern review (Stern 2006) between 450-550 ppm CO_2e, higher than the latest figure of 500 ppm CO_2e he suggested in June 2008[4]. However, more recent analysis by our Tyndall Centre colleagues suggests that these stabilisation levels require much more effort from the developed countries than is currently being contemplated. On a

[4] See http://www.guardian.co.uk/environment/2008/jun/26/climatechange.scienceofclimatechange?gusrc=rss&feed=environment

global basis, this effort needs to go well beyond the emissions reductions of 2.5–3% per year that is suggested by the Stern Review and Defra (Anderson, Bows et al. 2008).

There are other options that we could have used with different concentration targets as the 2007 IPCC projection has a high chance of pushing global temperatures above 2°C. One could argue temperature increases above this level are much more likely to lead to more serious, irreversible impacts (European Commission 2007). To have a much higher probability of confining temperature increases within 2°C, a smaller global cumulative emissions budget would be necessary. For example, Meinshausen predicted the world could emit around 400 GtC in this century with about 50% probability of an average temperature rise of over 2°C. This would require stabilising GHG concentration in the atmosphere at 450 ppm CO_2e in 2100 (Meinshausen 2007). In an earlier prediction, Meinshausen suggested even lower cumulative emissions of 387 GtC over this century, which would lead to a less than 30% probability of 2°C rise. In this second case, the concentration of greenhouse gases would have to peak at around 475 ppm CO_2e before declining to and stabilising at 400 ppm CO_2e (Meinshausen 2005). There are also other suggestions like that by Jim Hansen, senior climate scientist of NASA, who argues for stabilising at 350 ppm CO_2 or less in the long term is necessary "to avert disastrous pressures on fellow species and large sea level rise" in his famous letter to President Obama[5].

This illustrates one of the difficulties of developing carbon emissions scenarios: the science of climate change, and the urgency and extent of action required to meet stabilisation goals are continuously evolving. During the time taken to conduct the research that led to this report, delays in action by the world's economies mean that the allowable carbon budget is being used up, leaving progressively less emissions for future years. A practical problem with using lower global budgets is that they make it more difficult to develop a plausible global emissions pathway. Within this, pathways for individual countries including China can be very challenging and difficult to analyse. For example, the rates of decrease in emissions would either have to be very high (with emissions beginning to fall very soon) – or alternatively, China would need to be allocated a larger share of global cumulative emissions.

For these reasons, we have chosen a larger global emissions budget. This is not to say that we agree to accept a higher risk of temperature rise, but to illustrate the challenging task we face. With a higher chance of causing severe impacts, it should be recognised that adaptation to these impacts will also be much more important than under scenarios where global emissions are more constrained. As this paper will go on to show, the possible pathways for China's emissions under this larger global budget are still challenging enough. Furthermore, this reinforces the calls by many scientists and indeed the Chinese government that adaptation to serious climate change should receive much more attention.

Which apportionment method?

Although the latest IPCC report recognises the importance of focusing on cumulative emissions (IPCC 2007a), there is no consensus on how to apportion these emissions among countries. This is one of the most controversial and debated issues in the climate change negotiations, particularly with respect to a possible 'post 2012' international regime (Böhringer and Welsch 2006). There has been significant discussions in the climate change

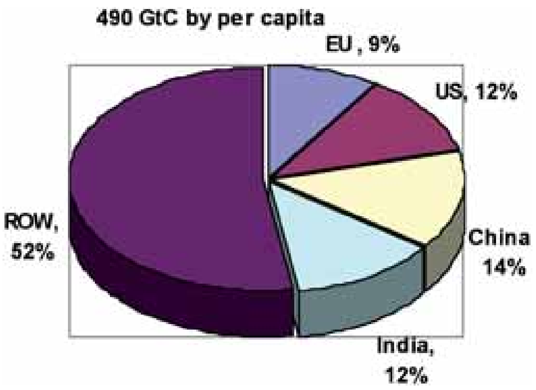
[5] His letter "Tell Barack Obama the Truth – The Whole Truth" is available at http://www.columbia.edu/~jeh1/mailings/20081229_Obama_revised.pdf

literature of different approaches to this question (Rose and Stevens 1993; Grubb 1995; Ridgley 1996; Rose, Stevens et al. 1998; Gupta and Bhandari 1999; Metz 2000; Leimbach 2003). Two of them are briefly discussed here, the equalisation of emissions per capita and the equalisation of emissions per unit of GDP.

The equal emissions per capita approach has been developed following the concept of equality using a Contraction and Convergence (C&C) mechanism developed by the Global Commons Institute. The basic principle is to entitle the same level of carbon emissions to each person in the world. Under this approach, emissions in many developing countries would be allowed to rise from current levels whilst all developed countries would need to reduce emissions. Some have pointed out that this approach is not as equitable as it seems since it fails to address different personal needs that are associated with existing natural and cultural living conditions (Leimbach 2003).

The second approach focuses more on global economic growth and efficiency. It aims to equalise carbon emissions per unit of GDP generated in different countries. This emphasises on equal carbon productivity and would therefore provide a strong motivation for countries to try to decouple economic growth and carbon emissions. However, it provides developed countries with some advantages as they usually have higher energy efficiency level hence a better starting point. For some, this is "equivalent to penalising the developing for their later progress" (Rose 1992). Gupta and Bhandari (1999) proposed an approach that tries to combine the per capita and carbon intensity approaches.

We decide to use these two apportionment approaches to generate the boundary for China's cumulative emission budget in the 21st century in our scenarios. It is worth noting that we do not expect actual emissions to conform to these budgets. We have simply used them as a way to generate a distinctive range of cumulative budgets for China in the 21st century, which will have significantly different implications. The global shares of cumulative emissions for some major emitters in the 21st century under the two apportionment approaches are shown in Figure 5.



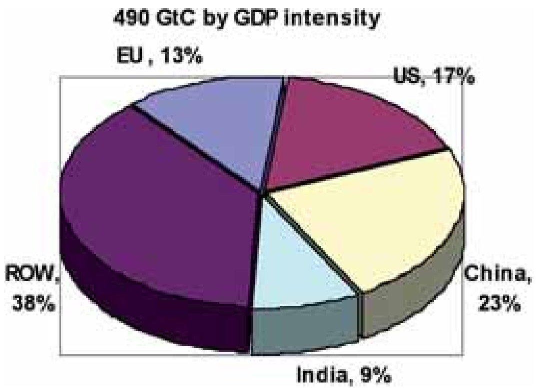


Figure 5: Shares of cumulative emission under two approaches

- Contraction and convergence (C&C) based on equal carbon emission per capita is used to generate budgets for two of our four scenarios. Under this approach, global emissions per capita will converge by 2050 and then contract at the same rate to the stabilisation level. Population change in different countries will not affect their global share after 2050.
- Contraction and convergence (C&C) based on equal carbon emissions intensity of GDP Purchasing Power Parity (PPP) is used for the other two scenarios. Similar to the first one, this approach converges to same level of carbon emissions per unit of GDP PPP, referring to the same carbon productivity across the globe. Then emissions will reduce at the same rate globally to the stabilisation emission level. Similarly, changes in GDP growth after 2050 will have no impact on each nation's share.

Cumulative emissions budgets for China

It is clear that the two critical factors that will determine China's cumulative emissions budget within this analysis are the relative growth rates of population and GDP.

Within all scenarios, the population growth of China in the four scenarios follows the median population projections from the United Nations (UN 2005). It states that China's population will slowly increase at around 0.4% p.a. from 1.3 billion in 2003 to 1.44 billion in 2030 before declining. China's population will be overtaken by India around 2035, whose population increases twice as fast as China between 2000 and 2050. In 2050, China's population will be around 1.4 billion while India hits 1.5 billion, with a total 9 billion world population. Using these figures and the global cumulative emissions budget discussed above would give China a budget of **70 GtC** over the 21st Century.

The GDP data used in this research is based on a purchasing power parity (PPP) approach. This equalises the carbon productivity of each country, taking into account differences of price. The national data of GDP PPP is taken from the World Development Indicators 2006 (World Bank 2006). Predictions of economic growth are based on estimates in the IEA's World Energy Outlook 2006 for 2003-2030 (IEA 2006a), and from the IEA's Energy Technology Perspectives 2006 for 2030-2050 (IEA 2006b). Note that GDP growth is only fixed while allocating China's cumulative emission budget. The actual rates of GDP growth will then become a variable in each scenario to elaborating the different pathways of emissions over time. This approach allows a cumulative emissions budget of **111 GtC** for China in the 21st Century.

From budgets to trajectories

Whilst these two methods have provided two distinct carbon budgets for China, the scenario development process still includes significant room for manoeuvre. We did not expect China's annual carbon emission to follow exactly the C&C approach. The pathway taken by China's annual emissions over time is fully flexible in our scenario as long as the cumulative emissions budget is not exceeded and the annual emissions in 2100 are the same as the annual emissions at stabilisation. In other words, the two chosen apportionment approaches do not constrain China's actual emission pathways over time. This leaves scope for our scenarios to reflect different assumptions about economic development, energy use and emissions.

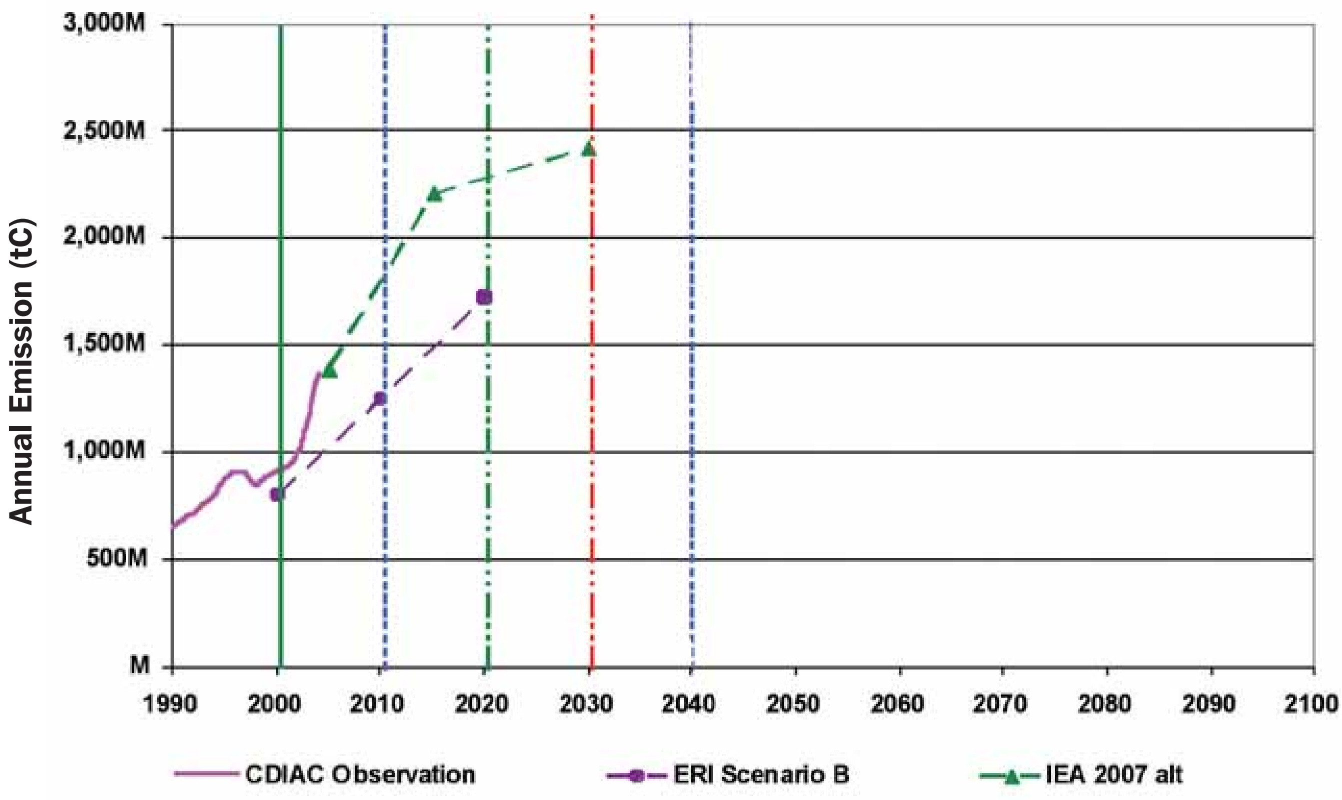


Figure 6: Carbon emissions in China since 1990 and projections by IEA and ERI

The next step is to outline four carbon emission pathways over time that are consistent to these two budgets. Following discussions at our second stakeholder workshop in London, we used medium-term emissions pathways that have already been developed by Chinese and international organisations as the first step towards decarbonisation in China. Our analysis will then see whether these pathways are compatible with the carbon budgets for the entire century that were outlined above. The two medium-term pathways we have chosen are the International Energy Agency's alternative scenario in the *World Energy Outlook (WEO) 2007: China and India Insights* (IEA 2007a) and scenario B of *ERI 2020* (Dai, Zhu et al. 2004).

The latter pathway was regarded at that time as the most likely scenario and incorporates an official Chinese government target of quadrupling economy size between 2000 and 2020, whilst energy demand just doubles. Each of these two pathways can be combined with both of our cumulative budgets to yield a total of four scenarios. The two medium-term pathways are illustrated in Figure 6 along with China's historical emissions from the dataset of the Carbon Dioxide Information Analysis Center (CDIAC) between 1990 and 2004. Inevitably the observation data is not entirely up to date as we used the 2004 data[6] as the last year of observation. China's carbon emissions have continued to rise in the last few years.

[6] CDIAC now has updated data of China's Fossil-Fuel CO2 Emissions for 2005, but it is too late for us to incorporate the update in the scenarios.

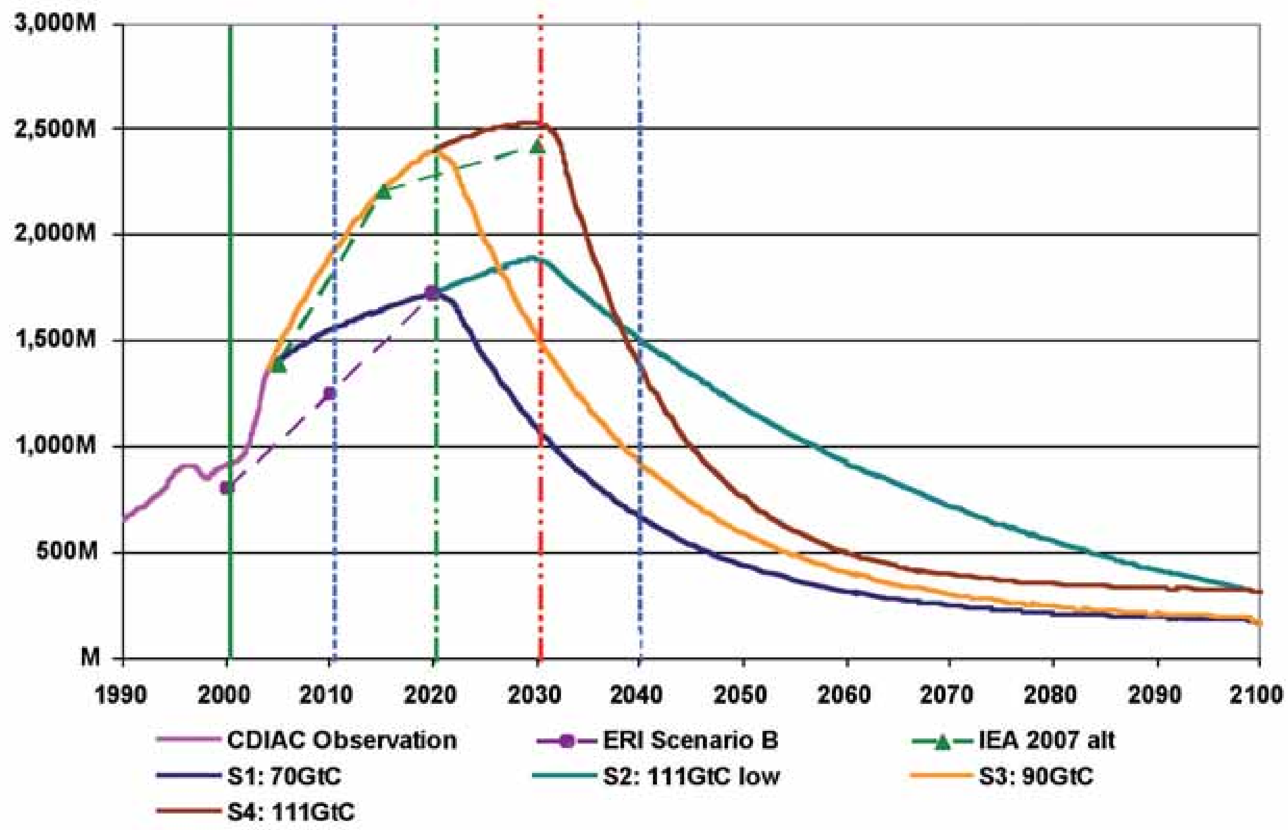


Figure 7: Carbon emissions in China: Historic data, projections and Tyndall scenarios

It therefore should be borne in mind that the actual challenge could be even greater than that revealed by the scenario analysis because more of the emissions budget has already been used since 2004.

The IEA's alternative scenario (IEA 2007a) for China takes into account the energy and climate related policies that have been considered by the Chinese government. This scenario "*illustrates how far policies currently under discussion could take us and assesses their costs*" (IEA 2006a, page 49). However, the pathway described by this alternative scenario does not show any dramatic change in China's carbon emissions growth during the next two decades. We have therefore used this pathway to illustrate the impact of relatively incremental changes on China's economy and energy system until 2020.

The original basis for our second medium term pathway, ERI's scenario B, was described as "a detailed interpretation of the sustainable economic and energy development for the 10th Five-Year Plan and the following 10 years" (Dai, Zhu et al. 2004, page VII). However, when it was produced in 2004, the ERI scenarios did not anticipate the sudden surge of China's energy demand and carbon emissions, particularly after 2003. This has occurred as a result of rapid growth in industrial sectors and a structural shift within industrial sub-sectors towards heavy industries such as steel and cement (Lin, Zhou et al. 2008). As a result, the 2010 estimate for carbon emissions in this scenario was already exceeded in 2004. However, despite that, we use their emissions estimate for 2020 to derive a medium-term pathway that employs a rapid and significant change in China's industrial and economic structure, and the consequent carbon emissions. This is a feature that participants in our first stakeholder workshop in Beijing were particularly keen to explore. It assumes a brake in the expansion of heavy industry and reduces overall energy intensity quickly. Derived from the medium-term target of quadrupling economy with doubling of energy demand between 2000 and 2020, this medium term pathway is also in line with the Chinese government's short-term target of reducing energy intensity by 20% by 2010.

For China's annual carbon emission pathways, the trajectory of China's carbon emissions starts from CDIAC data for the period 1990-2004, then the two medium term pathways are followed until 2020 at which point each divides into a further two pathways – giving us our four scenarios. All four pathways are shown in Figure 7.

Before describing each individual scenario pathway in more detail, it is worth commenting on some of the choices that have been made here. First, the medium-term pathways have only been followed to 2020. This maximises the chance that the scenarios will remain within their carbon budgets and also leave room to apply different features to each scenario.

A second point is that each scenario includes a peak in emissions followed by a declining trajectory to remain within its carbon budget. This decline is designed so that the pathway is consistent with the scenario's cumulative emission budget and reach the stabilising annual carbon emission level in 2100, and the rate of decline for each is determined by how much of the budget has been used before the peak.

Finally, the peaking years are between 2020 and 2030 in order to balance practicability and flexibility. A peak earlier is thought to be unfeasible while a later peak would make it too difficult to remain within the cumulative emission budgets. Even this choice of emissions peak necessitated some adjustment to our carbon budgets. In the case of the medium-term pathway described by the IEA with an emissions peak in 2020, it was not possible to follow this pathway while staying within the 70 GtC cumulative budget for the whole century due to the large emissions accumulated before the peak. We therefore increased the budget in this scenario to 90 GtC just to ensure the scenario could still be feasible. The stabilisation level at the end of the century remains unchanged. The additional emissions budget under this scenario could imply a possibility of delayed international climate agreement, or delayed action to curb China's carbon emissions due to a more incremental approach.

5. Trajectories in detail: implications for future energy pathways

Crucial to each scenario's carbon emissions pathway is the story that implicitly lies behind the changes in emissions. This will aid our detailed elaboration of the pathways, and illustrate how annual emissions from different sectors of China's economy will fit within the overall trajectory of each scenario. Table 1 summarises the key features of each story – including the year in which carbon emissions peak, the innovativeness and openness of the future Chinese economy, and the social preference between efficiency and equity. A narrative storyline is provided for each scenario which depicts the key trends in the scenario.

Among various differences that differentiate the four scenarios, one of the most important distinctions is the speed and extend to which the current Chinese economy is transforming into a much more innovative and knowledge based economy that has strong and dynamic high value-added industries and services. Another key distinction is the societal preference between social equity and economic efficiency, i.e. to what extent income disparity is addressed as a more serious issue than income growth.

The first distinction lies in the nature of innovation that shapes the future Chinese economy. We use these features to explore the possible implications of Chinese government's current efforts to rebalance the sources of China's economic growth (Wen 2008). This is a particularly evident change in the 11th Five-Year plan for national economic and social development since 2006, which has a strong focus on promoting science and technology innovation to boost future economic growth. Scenarios 1 and 2 describe futures in which rebalancing has been more successful and more rapid – whilst in scenarios 3 and 4 this process has been slower and less successful. The first two scenarios are characterised by more radical change, and a more pronounced shift away from heavy and conventional industries towards more value-added manufacturing and the provision of a service based economy.

	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)
Cumulative budget	70 GtC	111 GtC	90 GtC	111 GtC
Medium-term pathway	ERI 2020	ERI 2020	IEA	IEA
Year of emissions peak	2020	2030	2020	2030
Population growth rate	Same in all scenarios following the UN 2004 prediction			
Nature of innovation	highly innovative, tendency for radical technical change	strong science and technology advance; but slower diffusion	significant technical change – cumulative, incremental process	incremental innovation, mainly in legacy industries
Equity and Efficiency attitude	strong preference for social welfare and equity	globalised market and economic efficiency driven	inward investment and against communal disparity	focus on market and growth, individual success

Table 1: General characteristics of the Tyndall Centre scenarios

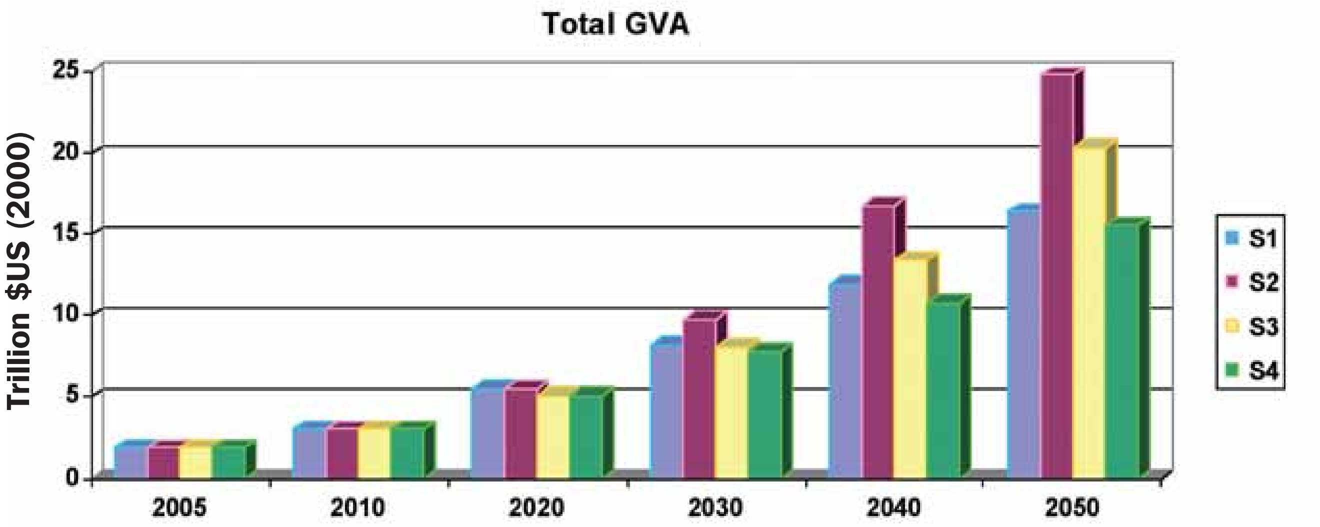


Figure 8: Growth of total Gross Value-added of Chinese economy in each scenario

A major difference between scenario 1 and 2, and between scenario 3 and 4, is the attitude to disparity within the future society. With a communal attitude supporting equal rights and opportunity within the community, scenario 1 and 3 are societies with stronger preference for public welfare and inward investment, and with less income disparity than scenario 2 and 4. As China's economy rapidly grows over the last two decades, income disparity and the equity issues are becoming ever more acute. The most commonly used inequality indicator, the Gini index, has risen quickly in China since the economic reform. China has an index of 46.90, positioned at 93 out of the 126 countries surveyed (UNDP 2008). Despite the criticism of the general accuracy of the Gini index's, at its very least this figure gives a hint of China's deteriorating income disparity over the last two decades. Together with environmental issues, income disparity is believed to be a main source of increasing social unrest and an imminent instability threat. So it will stay high on the Chinese government's agenda. It has been particularly pointed out in the Chinese President Hu Jintao's keynote report at the 17th National Congress of the Communist Party of China in 2007 as well as in the 11th Five-Year Plan.

These differences described above have shaped the four scenarios to make them very distinctive from each other, and hence no scenario is intended to be claimed as 'the best'. Nevertheless, the four scenarios are in general divided by the two critical issues that challenge China's future development path, innovation and income disparity. Each of the scenarios represents a particular combination of potential responses that China might implement to address these two issues. It is not up to the authors, nor is our intention to suggest the best development path, but to help inform the potential economic, energy, environmental and social implications of each choice, particularly those of global importance to the global challenge of combating climate change.

Cross-scenario results

Economic Growth

With different carbon emission and economic growth trajectories, these four scenarios lead to different GDP growth of Chinese economy. The annual GDP growth rates between 2005 and 2050 on average vary between 4.8% in S4 and 5.9% in S2. Over 45 years time, this leads to a rather large difference in GDP size, as shown in Figure 8. The economy in S2 will be more than 13 times large as that of 2005, while in S4 it

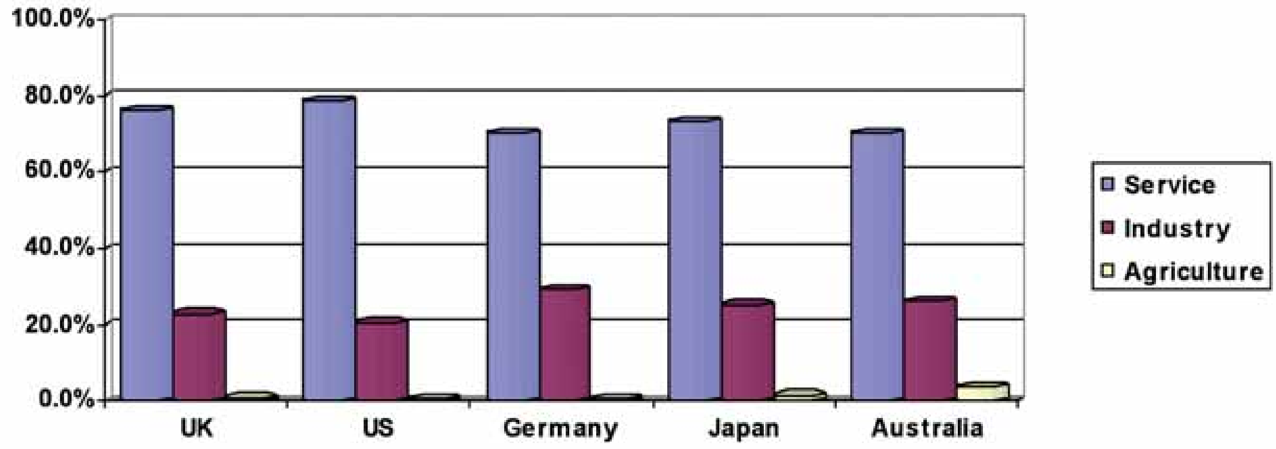


Figure 9: Economic structure of current major OECD countries

will be just 8.24 times larger. The size of the economy is measured by the total Gross Value-added (GVA) from agriculture, industry and service sectors combined, which thereafter is used as a proxy for GDP. The Chinese economy will increase from $1.89 trillion (constant 2000 US$) in 2005, to $15.54 trillion in S4 and $24.86 trillion in S2 respectively. S1 has similar GVA size as S4 while S3 ranks in the middle.

Economic Structure

One of the main reasons behind the different size of the Chinese economy in each scenario is the variance in the composition of each economy. The economy in the future is driven by the progress of science and technology advances as well as the social preferences. In common with many of the major developed countries, (see figure 9) services and commerce will eventually become the largest economic sector, accounting for between 60% and 80% of GDP in our scenarios. But there is also major difference in the structure of industries. The whole industry is divided into four sub-categories: heavy industry, conventional industry, high technology and valued added (HTV) industry and the energy industry that mainly involves electricity generation. The heavy industry includes iron and steel, petrochemicals, non-ferrous metals and minerals etc., while the conventional industry includes manufacturing industries that are not energy intensive nor high value-added.

The composition of the Chinese economy in each scenario is illustrated in Figure 10. Service and HTV industry are the sectors that would enjoy the largest growth from now to 2050, but the growth varies across scenarios. S1 and S3 have the largest share of the economy contributed by the service and commerce sector: about 75% and 78% respectively. Industry overall accounts for 20% in these two scenarios and between 3 and 5% is from agriculture. S2 and S4 will see a larger share from industries, but with different compositions. With significant progress in science and technology innovation and an innovative society, HTV industry will account for 75% of all industry in S2 in 2050, while in S4 it is more equally shared by heavy, conventional and HTV industries. Services will account for 65% to 70%

Figure 10: Different economic structure of each economy

of the economy in these two scenarios and 3% for agriculture. However, with the lowest service share (<65%) and largest industry share (33%), S4 is different to the other 3 scenarios and all today's major developed economies. This reflects some consideration that given relative size of China, it is possible that China will be unable to largely rely on outsourcing of manufacturing to other less developed countries in the future - at least not as much as the current OECD countries have outsourced to China. There will be also much less population in developing countries to support these industries after today's emerging economies turn into developed economies. Therefore a large share of heavy and conventional industries will remain in China within scenario 4 to support domestic needs.

Energy Demand

Similarly, there is also wide variance in total primary energy consumption (TPEC) within the four scenarios, as shown in Figure 11. S1 has the least energy consumption in 2050 among the four, at 1886 million tonnes of oil equivalent (Mtoe) compared with 1638 Mtoe in 2005. S4 will consume 3232 Mtoe. However, these levels of energy consumption do not stem from linear growth in any scenario, with growth, decline and stabilisation at different stages. Due to different roles that research and development, demonstration and diffusion (R&DDD) of low carbon technologies has in reshaping the general economy and energy system in each scenario, the picture is slightly different when it comes to final energy demand. S2 instead overtakes S4 and ends up with a higher final energy demand in 2050 due to less energy transformation and transition losses. The final energy demand in S3 also becomes closer to that of S1 for the same reason.

Energy Structure

Apart from the variety in demand levels, the fuel sources of TPEC are also very different in each scenario and over time. Figure 12 shows the energy mix evolution in each scenario. Starting from the same point in 2005, differences can already be seen between S1&S2 and S3&S4

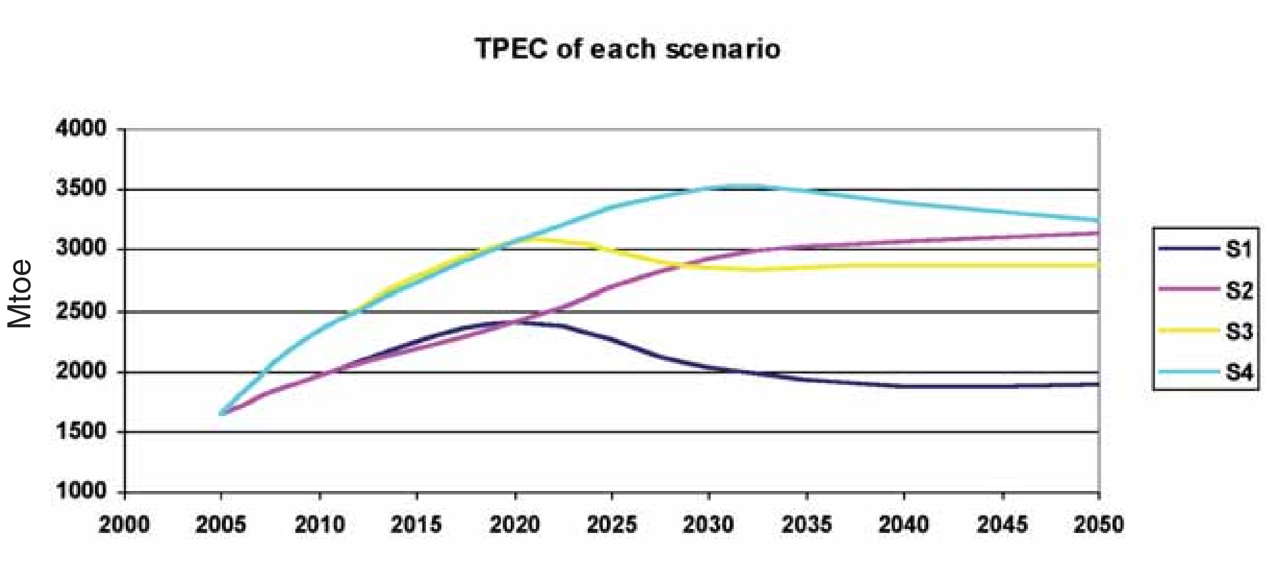
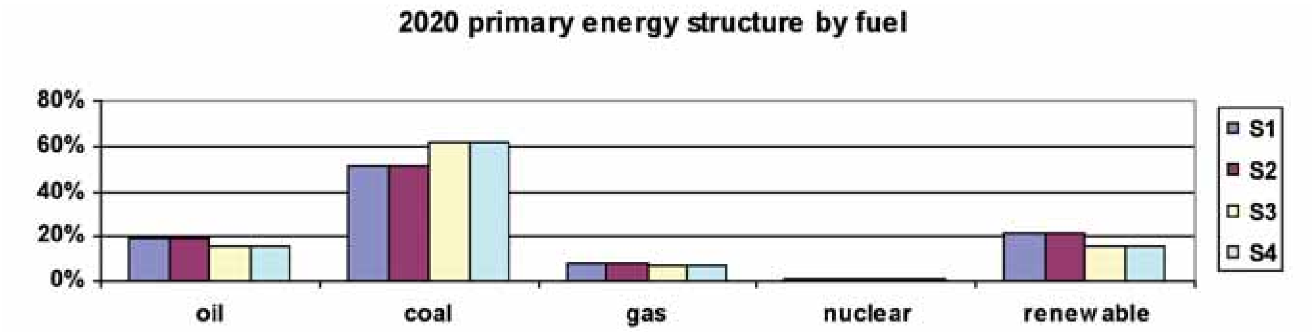


Figure 11: Total primary energy consumption of each scenario from now to 2050



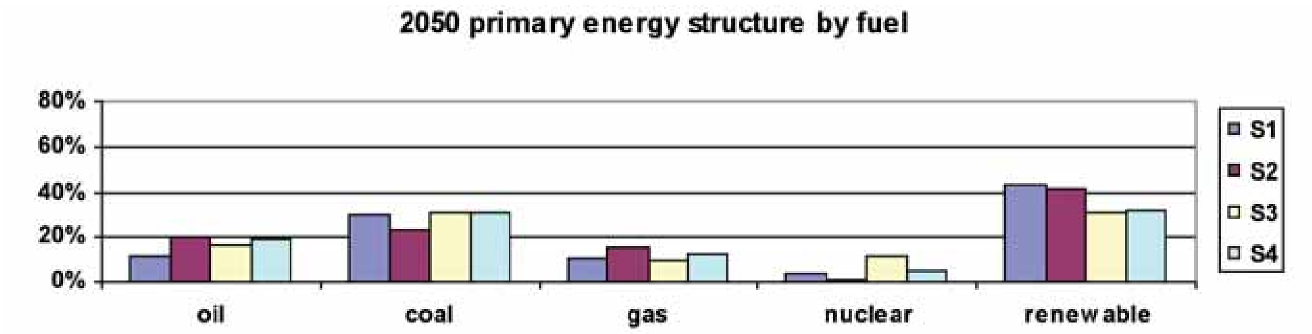


Figure 12: comparison of primary energy demand of scenarios in 2020 and 2050

following the two different medium-term pathways. In S3 and S4, renewables managed to provide 15% of total primary energy consumption in 2020, as planned by the Chinese government, while S1 and S2 will increase the share to 20% due to a stronger promotion and development of renewable energy. 2050 will see renewable energy playing a much bigger role in China’s energy system, but will also see a more diverse energy structure. Coal will reduce from more than 60% in 2005 to around 30%, while oil and gas continue their steady growth in the energy mix. Nuclear has the most diverse picture, nearly negligible in S2 and more than 12% in S3. This reflects a choice between advanced renewables such as wind and solar PV and nuclear for low carbon energy supply. But the scenarios show that it is difficult for nuclear to play a major role in the Chinese energy system, even with a huge expansion that dwarfs the experience of French nuclear power. The details will be elaborated more in the specific results of each scenario later in this section. Even though each scenario leads to a similar level of renewables in the energy mix, there is still large variance in technology choice within the renewable options, as well as in the way they are deployed (e.g. in centralised facilities and/or small scale micro-generation).

Power Generation

The power generation sector has been the fastest developing sector in China since 2000. Although largely dominated by coal, with power generation capacity more than doubling in just 8 years, there is a great deal of room within the

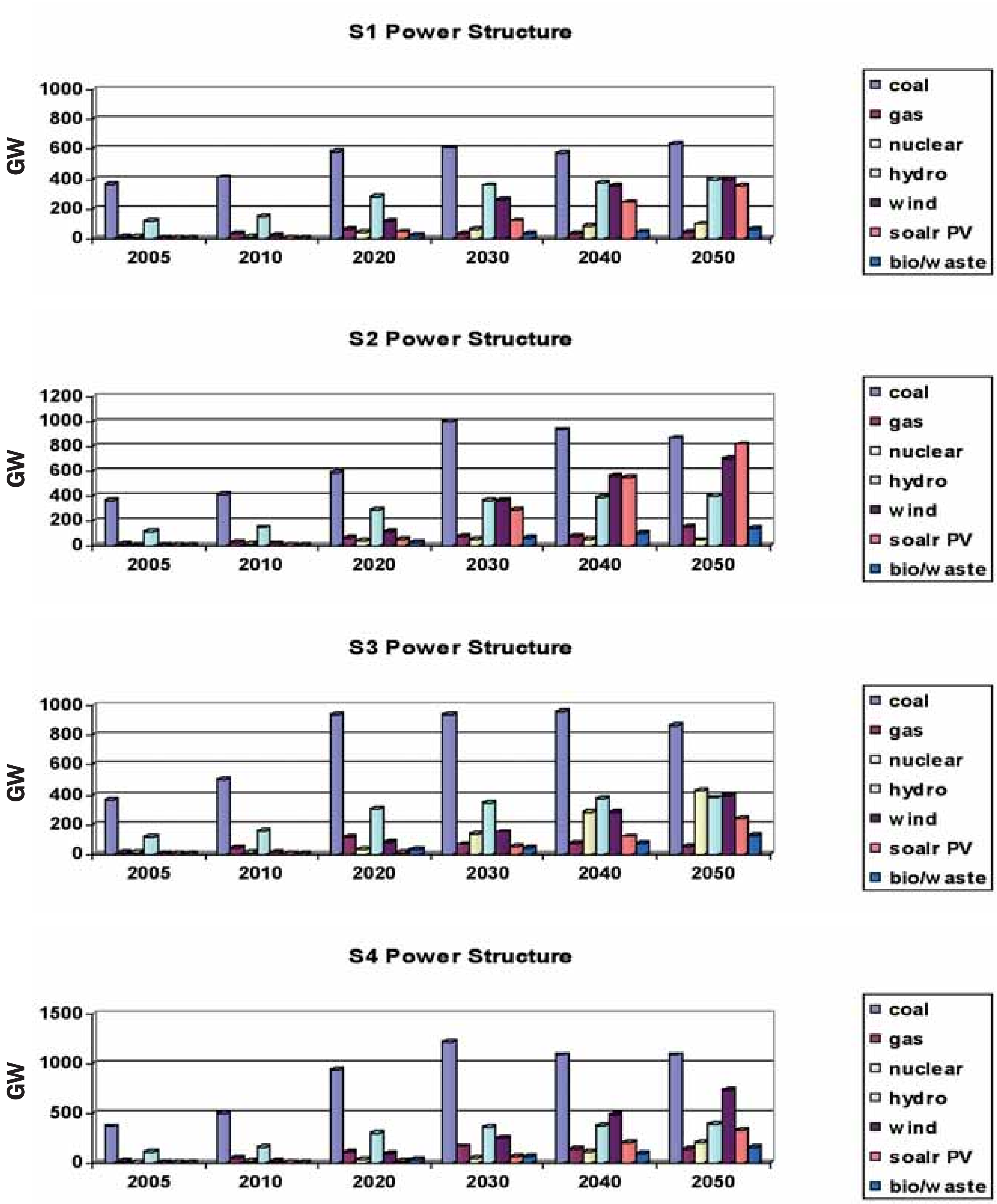


Figure 13: Power structure of each scenario over time

scenarios for renewable sources of electricity to grow. The evolution of power generation capacity in each scenario reflects the variable electricity demand for economic growth, but also indicates our judgements about technology choice within the storyline of each scenario. The details are shown in Figure 13. As discussed above, S2 will have significant progress in both wind and solar PV, which are of comparable size to coal fired power generation by 2050. Wind power will increase at about 10% p.a. or 16 GW every year between 2010 and 2050, and 16% p.a. for Solar PV during the same period. This figure is 15% higher than the high range development target in the China Wind Power Report 2008 (Li, Gao et al. 2008) but we believe it is consistent with the innovative storyline of S2. S3 sees significant developments in nuclear power capacity to become the second largest source of electricity. The 400 GW nuclear power generation capacity deployed by 2050 within S3 contributes up to 30% of the grid electricity. S1 has the smallest power generation capacity among the four, with only about 600 GW from coal and 400 GW each from wind, solar PV and hydro. As we mentioned in earlier sections,

China's coal fired power capacity already reached 600 GW in the end of 2008, therefore transitioning to S1 would require significant plant retirements to offset new capacity additions. S4 instead has the largest coal fired power capacity, over 1200 GW in 2030 and then a decline to 1086 GW by 2050. Apart from that, S4 also includes a large portfolio of renewable electricity generation technologies due to its large electricity demand. Among the four scenarios, it has the largest generation capacity in coal, bio/waste and wind, and the second largest generation capacity in hydro, gas and nuclear. Unsurprisingly a large amount of coal and gas powered generation has to be equipped with carbon capture and storage (CCS) so that the carbon emissions could be abated to comply with the emissions budget. This is almost as critical for S3 due to its smaller budget but S4 faces the more challenging task to bring about a much quicker and larger deployment in its massive power system.

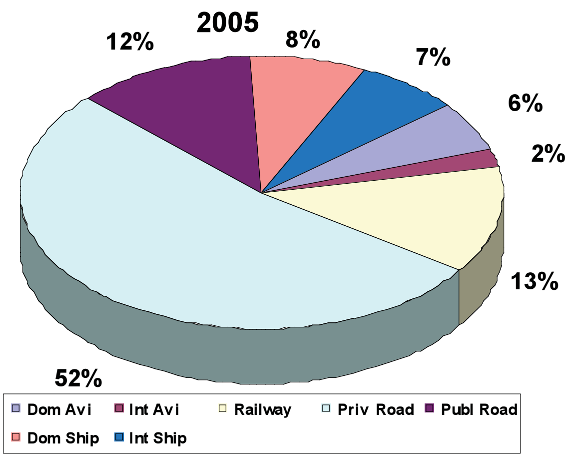
Transport

The differences among the four scenarios are less prominent in the transport sector, as China's transport in general is still well behind the level of developed economies. Even for the widely-known story of China's fast growing private car ownership, the national average is only 17 cars per 1000 people (IEA 2007a) in 2005 compared with over 700 in the United States and 400 to 550 in European countries (IEA 2007b) in 2004. Within China, there is a big variance between rich coastal cities and the inland less developed provinces. Both domestic and international aviation have experienced some dramatic increases over the last few decades. However they are still lagging behind the booming demand for mobility that has been increasing with income over the same time, particularly because of the laggard infrastructure. With similar size of territory or less, China had 186 major airports[7] in 2007, compared with 415 in the United States, and 457 in the European Union (CIA 2008). It also has much less extensive railway infrastructure, at 75438 km in 2007?only one third of that in the European Union or United States (CIA 2008).

Therefore, there is unsurprisingly significant growth in almost all modes of transportation in the four scenarios, although the exact pattern varies depending on the preferences of each scenario. Variations reflect preferences between public and private transport, between railways

[7] We only counted the airport with paved runways longer than 2438 m so to avoid counting in private and military airports, but this cannot be guaranteed.

and private cars, etc. The 2050 fuel consumption from transportation in each scenario is shown in Figure 14. This results from combined drivers of mobility growth, technology advance, and transportation preference. The unique feature of each scenario is still obvious. S1 has high percentage of public road transport and S3 has more from railways. Although both reflect a strong preference for public transport, public road transport works better in S1 in which most people are living in a large number



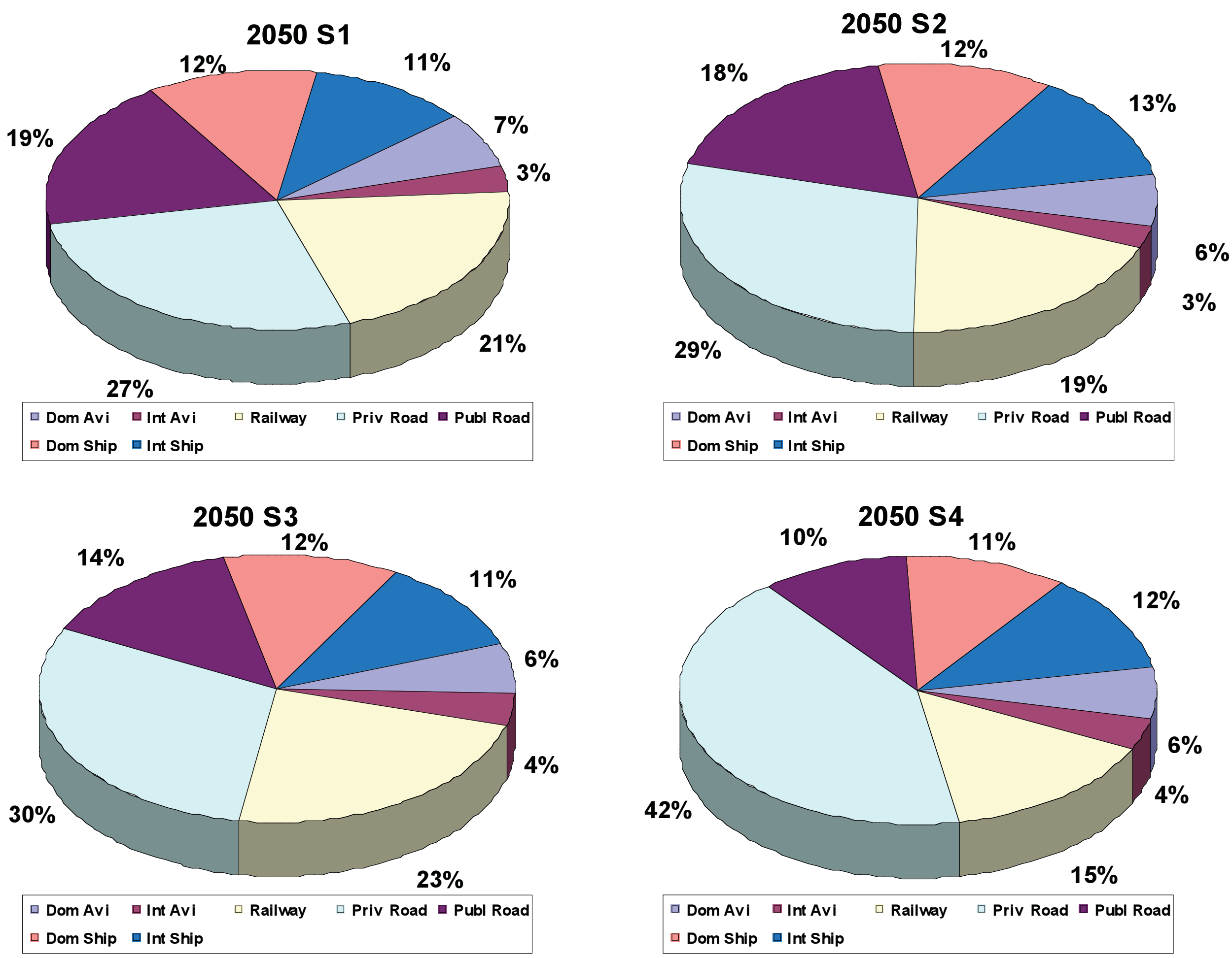


Figure 14: Energy demand of transportation in each scenario

of small cities and countryside areas while railways are better for the majority population in S3 that lives in a few large cities and a number of medium cities. The population distribution and density patterns are discussed in more detail in later in this section. S2 has a similar transportation system to S1, only having a bit more private road transport. But note that this is the scenario with the highest economic growth and highest mobility, so the public transport system including railways will be much larger than that in S1. S4 has the largest share of private road transport and a relatively weak public transport system, and as a result the transport system accounts for nearly 60% of S4's total carbon emissions in 2050.

Household

Household energy use included large amounts of micro renewables in 2005. However these are not the "modern renewables" such as solar and wind. The majority is solid biomass like fuel wood. Coal still persists as an important fuel source in household energy use despite its use having been banned in many cities in China. Grid electricity has increased exponentially over the last two decades with an ever rising electrical appliance ownership in China. The rising number of air conditioners in coastal areas was partly responsible for the electricity shortages in 2004 and in subsequent summers. District heating is another important form of household energy.

The four scenarios include quite different levels of household energy demand, but the general trend is similar. There is a strong growth in grid electricity in all scenarios, as well as a moderate increase in the share of gas together with a quick decline of coal use, which reduces the share of coal to less than 7% by 2030 and totally phases it out by 2050. The change of household energy use is shown in Figure 15.

The development of micro renewables is much more complicated than is shown here. Traditional biomass is declining all the time at different rates in the four scenarios. At the same time, other renewable energy sources including solar water heaters, small scale off-grid combined heat and power (CHP), advanced biomass and biogas use, more advanced solar PV panels and roof-top wind turbines are all developing quickly in each scenario at various rates and with various priorities. As a result, the micro renewable energy use will increase in the first two decades from now to 2030, although its share has fallen from 65% to 30-50% during the same time. Between 2030 and 2050, the micro renewable energy use declines gradually along with overall household energy demand in all scenarios as a result of the following factors. First the household energy demand will start to plateau and decline with successful demand side management (DSM) and continuous energy efficiency improvements in household energy use. Second is the continuing decline of the use of solid biomass, coal and oil in households, which becomes negligible by 2050. The third is the wide deployment of advanced micro renewable technologies. Energy used in the household is more and more generated within the house or local community, which in turn increases efficiency and reduces losses. For example in S1, the electricity generated from micro renewables in 2050 will account for 37% of total electricity use in the household, and micro renewables will contribute 45% of the total energy use in the household.

Figure 15: Fuel sources of household energy demand

Industry

Industry is the largest sectoral energy consumer in China, therefore its structural change has very significant implications for China's future energy consumption and consequent carbon emissions. This is particularly the case now that heavy industries account for nearly 60% of total industrial energy demand, while industry as a whole accounts for more than two thirds of China's total energy demand (NDRC 2007b). In common with their GVA, the energy demand of various industries are significantly different. This distribution of demand is strongly related to the structural change of industry, which is illustrated in Figure 16. In 2005, the majority of energy is consumed by heavy industry, followed by the energy industry and conventional industry.

In S1 and S2, science and technology innovation will significantly boost the development of HTV industry. As its GVA increases over time as discussed in an earlier section, the energy demand of HTV industry will also increase fast. It will increase from about 60 Mtoe to 120 Mtoe in S1 by 2030, and to 180 Mtoe in S2. On the contrary, the figure is less than 100 Mtoe in S3 and S4. By 2050, the HTV in S2 will increase to account for nearly half of the total industrial energy demand while it generates more than 75% of total industrial GVA. It also accounts for one third of the industrial energy demand in S1, but only less than 20% in S3 and S4. Instead, heavy industry is still dominant in the industrial energy demand in these two scenarios, S4 in particular. 60% of

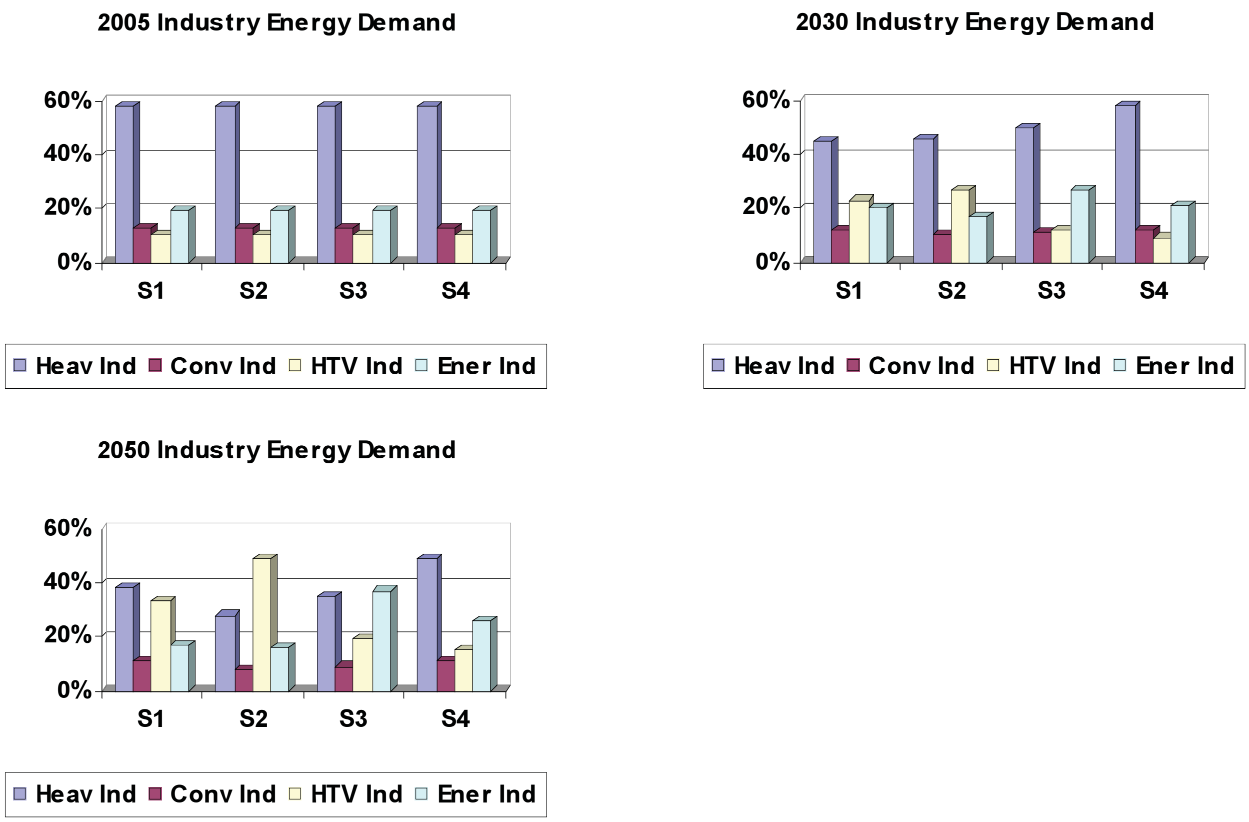


Figure 16: Change of industrial energy demand over time

industrial energy demand in 2030 and 50% in 2050 in S4 stems from heavy industry. As a result, the energy industry also becomes a larger energy consumer in S3 and S4.

However, these trends occur against a background in which the share of energy demand consumed by industry is declining in all scenarios as energy consumption in household and transportation grows much faster. By 2050, the household and transportation sectors will both account for 30-35% of total final energy consumption, similar to the share of industry. This is a similar energy consumption structure to current OECD countries. The fact that all four scenarios lead to similar energy structures by 2050 illustrates the significant future importance of controlling energy demand growth in the household and transportation sectors. This can be done by avoiding energy lock-in effects due to low housing quality and efficiency standards, poor public transport plans and high carbon footprint lifestyle. Without starting to address these issues now, they will become stubborn obstacles to reductions in energy demand in the future, and severely jeopardise efforts to remain within the cumulative emissions budgets used in our scenarios.

Scenario Specific results

Scenario 1: 70 GtC 2020

Highly innovative, domestic driven and service dominance economy; strong preference on social equity

This scenario has the smallest cumulative emissions budget for China based on an equal per capita approach. In common with the approach used to allocate the cumulative carbon emissions, the society in this scenario also gives more priority to social equity and welfare among the people. Addressing disparities and ensure equal opportunity in public services like healthcare and education to each member of society has been preferred to economic efficiency and income growth. Therefore to some extent the low GVA size and energy consumption in S1 is a choice rather than result (See Box 1). China's carbon emissions will peak in 2020 and then reduce to comply with the annual emissions budget in 2100. Nevertheless, GDP of S1 in 2050 will be 8.7 times as large as that in 2005. Carbon emissions will peak in 2020 at 1724 MtC (megatonnes of carbon = 10^6 tonnes), about 24% higher than the 2005 level, then quickly decline to only 30% of the 2005 level by 2050, at 435 MtC. Energy intensity of the Chinese economy will be reduced to 50% lower than the 2005 level by 2020, and is further reduced to 13% of the 2005 level in 2050. Carbon intensity of GDP will be reduced even more to only 4% of the 2005 level due to decarbonisation. The economy is highly innovative because of a strong promotion and pursuit of science and technology. With a quick and radical economic structural change, the service sector becomes dominant, accounting for 60% of the overall economy by 2020, compared with 42% in 2005, and it further increases to 75% in 2050. This is similar to the share of services in today's UK economy (Office for National Statistics 2007). But agriculture will still account for nearly 5% in 2050 compared with 1% in the UK due to higher contribution from rural development. Overall, the society is quite stable and harmonised with reduced social and economic disparities and comprehensive social welfare coverage.

Box 1 Demand Side Management and Behaviour Change

A strong feature in the scenario 1 is the low energy demand in general compared with the other 3 scenarios. As discussed above that the relatively small economic size and low energy demand in this scenario stems from a choice to place more emphasis on social equity and public welfare. The relatively low energy demand reflects a social preference for a greener and more sustainable lifestyle and higher environmental awareness, but is also a result of successful demand side management (DSM) of energy consumption, particularly in households and transport. With similar technological advances, this made a distinctive difference between S1 and S2 in the growth of household and transport energy consumption for same level of economic growth. For example, between 2020 and 2030 the income elasticity of household energy demand, measured by the responsiveness of energy demand growth to the change in the income of the people, is a quarter lower in S1 than in S2. This is particularly important for S1 to realise an early peak and quick reduction in emissions after 2020. In transport, the overall mobility growth in S1 is also smaller during the same period, with just half of the growth of S2 in aviation and 40% in private road transport. But note that this is overall mobility growth which has taken into account the higher economic growth in S2. Similar differences could also be found between S3 and S4, but of less prominence.

There is large potential to reduce energy consumption in both residential and non-residential buildings (Hinnells 2008a; Hinnells 2008b), as well as to provide energy more efficiently with lower carbon intensity. Many technologies that can enable this are already known, and some related to behaviour changes. But more understanding is needed of these technology innovations and their performances over time, which can only be learnt through small scale implementation that is supported by an appropriate regulatory framework and economic incentives before they can diffuse on a much larger scale (Watson, Sauter et al. 2006; Woodman and Baker 2008).

The Chinese government has started realising the importance of DSM and raising environmental awareness in people. Media, NGO and governmental led environmental and climate change campaigns have made some progress. A recent survey revealed that people in China showed a strong correlation between knowing about climate change and participation in environmental activities to protect the environment (Europe's World 2008). The Chinese government also published the 'Booklet of Public Energy Conservation and Pollutant Discharge Reduction' in 2007 to encourage and guide the general public to conserve energy in their daily life. But this is just a beginning for changing the lifestyle and consumption behaviour in China in a way that is compatible with low carbon development. It is important to start addressing it now to avoid social carbon lock-in[8].

[8] Carbon lock-in does not only apply to carbon intensive infrastructure and investment, but also applies lifestyles and activities with high carbon intensity. If people believe success means having an energy intensive 'American lifestyle', it could become a key part of an overall pattern of carbon lock-in that includes high carbon technologies and infrastructures, and associated institutions and policies.

Energy and power generation

In this scenario, with reduced growth in industry and agriculture, the overall energy demand growth within the Chinese economy is slow, at about 2% p.a. between 2010 and 2020, and declines slightly in the next decade before reaching a plateau after 2040. Energy will be supplied from a wide range of sources, and renewable energy will eventually overtake coal to account for the largest share of energy consumed by 2050. Renewables will account for about 43% of TPEC, including 11% from sustainable biofuel. Because of the pressure of emissions reduction, the use of coal across the economy will be gradually reduced and will be increasingly burned with advanced technologies. The share of coal in TPEC will reduce from more than 60% to 30% during the same period, while its share in total carbon emissions halved to 42% from 83% in 2005. In the power sector renewable energy, largely hydro power and wind, dominates nearly half of the electricity generation in 2050. This extends to 55% when off-grid generation is included. Wind will overtake hydro power in 2050 to become the largest renewable power source, accounting for one fifth of total electricity generation from its 400 GW installed capacity. Hydro follows with 18% of generation and nearly 400 GW and solar PV accounts for 10% of generation and 250 GW of capacity. Fossil fired power plants still account for 36% of electricity, but two thirds of them will be equipped with carbon capture and storage (CCS). Nuclear will contribute 8%, compared with 2% in 2005 and 4% in 2020.

Oil and gas will each contribute about 11% of TPEC, and 35% and 23% of carbon emissions respectively. Oil will still be important for transport, but demand increases will be moderated by efficiency gains and substitution from biofuel and electricity use in transportation. As a result, the share of oil in TPEC will drop slightly in 2050 to 12% from 15% in 2005. Overall energy demand growth will be much lower than it has been in recent years due to economic structural change, low carbon technology diffusion, stringent efficiency measures and significant demand side reduction within an environmental friendly society.

In power generation, coal will remain as the largest source of electricity until 2030-2040, but energy efficiency will have improved significantly, with replacement of small inefficient plants with the most state of art technologies. CCS technology will become available and a favourable option after 2020, depending on the price of coal. It will soon become a compulsory measure for coal-fired plants after that date to meet the need for curbing emissions quickly. Older coal-fired capacity that remains will be retrofitted with CCS where feasible. Power generation from natural gas is still small, and constrained by resource availability from both domestic and imported sources. Overall power generation will grow to over 4 times in 2050 of the size in 2005, with 80% growth in the installed capacity of fossil fuelled power plants. This is in the same range as the IEA's estimate of 3 times growth in total electricity generation by 2030, but significantly less than its estimate of 150% growth in fossil fuelled power plants in 2030 (IEA 2007a). Given the small carbon budget, CCS proves to be a critical technology to enable the reduction in China's carbon emission without much disturbance to the overall economic activity.

Among the renewable energy sources, a significant proportion of the renewables are from biomass, both CHP and onsite use like biogas, and hydro electricity, benefiting from growth in the agriculture sector. Wind power becomes another significant energy source assisted by technology advances and public support. PV has increased dramatically, particularly in off-grid and micro-generation power systems, but is still a small proportion of overall supply. Solar thermal for hot water and space heating prevails in Chinese households. Large scale renewables diffusion is accelerated by both financial incentives and technical progress. Some renewable technologies will become more economic than coal as the emissions budget tightens. Decentralisation also encompasses the provision of heat with widespread use of CHP powered by fossil and renewables for urban areas; while demand in rural areas includes significant amounts of biogas and solar thermal. Decentralised energy systems will provide a large share of household energy needs in 2050, comparable to that delivered though the central electricity grid.

Industry and services sectors

In S1, China will pass the phase of heavy industrialisation within the next few years, a vital development to allow a rapid transition from the current carbon emission trajectory. By 2030, the growth of energy and resource intensive heavy industry, such as iron and steel, petroleum chemical and non-ferrous metals will be reduced quickly, halving its share in the economy. Service and high technology and value-added (HTV) industries will embark on much faster growth. Both heavy and conventional industry such as machinery and textiles will still persist at levels to supply domestic needs. Overall, industry's contribution to GDP will gradually shrink from 45% in 2005 to 20% by 2050. Continuous improvements in energy efficiency and new materials technology supported by science and technology advances make heavy industries much more efficient and sustainable than today. With strong support and promotion in innovation and technology transfer, the GDP contribution of HTV industry increases from 9% to 11% and moves up along the value chain of production. The service sector is dominant in China's GDP yet it consists of large numbers of dynamic small and medium enterprises. A flourishing service sector offers wide and in-depth coverage to people's well being. Energy service companies grow particularly fast to offer both supply and demand side management. Agriculture accounts for nearly 5% of total GDP, the highest among the four scenarios, which is partly because of the development of high valued added agricultural products.

Households and personal transport

Energy demand in households and personal transport will increase with income and living standards, but at a relatively low rate because people in this scenario have a stronger preference for environmentally friendly housing and public transport. Environmental education and awareness will trigger behaviour and consumption changes in early years and make people more inclined towards a green lifestyle. People in S1 prefer to move out from crowded cities. A large proportion of the population is living in small cities and the countryside. New buildings are obliged to meet high energy efficiency standards and to maximise the integration of natural lighting and renewable energy sources for heating and power. Solar heating is the major heating system supplemented by other sources including fossil fuels and biomass. Old houses and flats will be upgraded and retrofitted to a similar level. Private car ownership has increased moderately but energy efficiency and alternative fuels are able to largely offset the increased emissions from this. People use more public transport particularly in cities and towns while in rural areas private transport is run on energy efficient and low carbon fuels. One strong feature in S1 is a decarbonised road transport system with advanced electric vehicles for both private and public transport. Electric and alternative fuel vehicles will become popular quickly and contribute significantly to emission reductions by 2030. This, partly attributed to Chinese government continuous support in R&DDD and promotion of electric vehicles, enables the Chinese auto industry to leapfrog its western peers with the growth of Chinese private car market (See Box 2). Similarly, demand for international aviation and shipping only includes modest growth in this scenario.

Nevertheless, households and transport will become bigger energy consumers than industry in S1, with about 30% each. The rest is made up of 26% for industry and 10% for services. Half of the gas is consumed in households for cooking and heating, while half of the oil is consumed by aviation and shipping. This is due to fuel switching in industry and a boom in electric vehicles for both railway and road transport. In 2050, electricity will meet around 75%, 60% and 76% of respective energy demand in railways, private and public road transport, see Figure 17. This is in addition to some 13%, 28% and 12% of energy demand from biofuels in these sectors respectively.

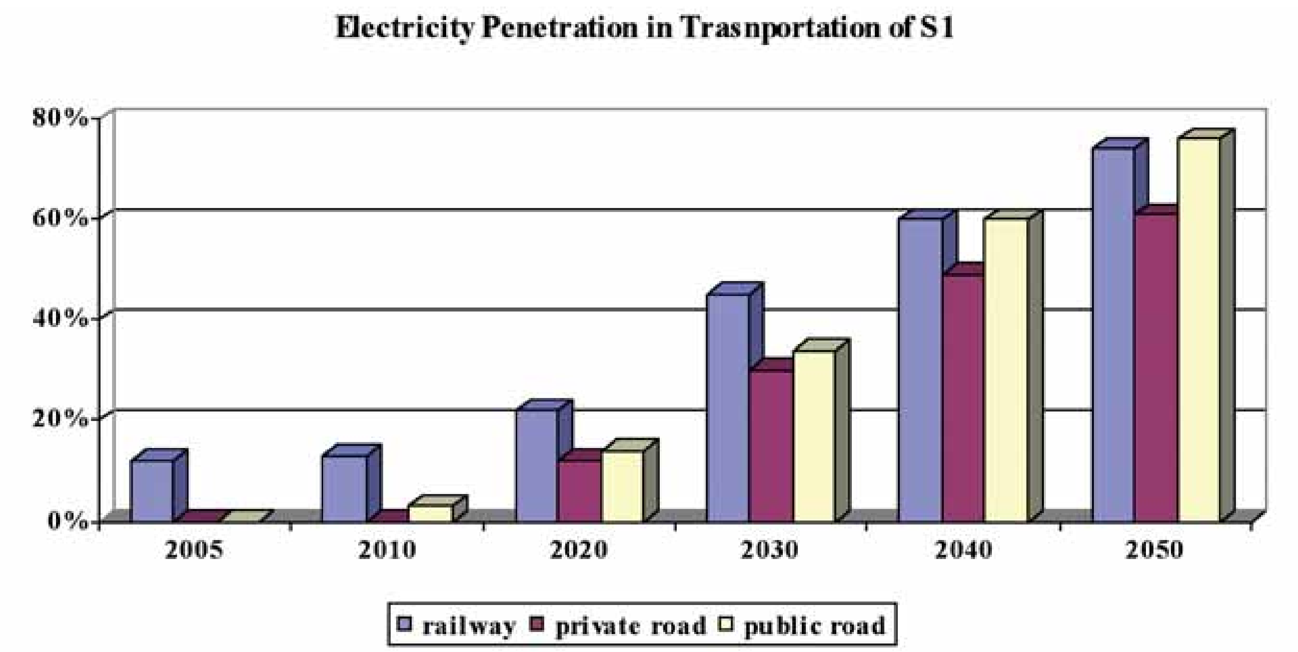


Figure 17: Electricity penetration in Transportation of S1

Box 2 China's Automobile Industry Leaps Forward in A Low Carbon Economy?

The Chinese government views the automobile industry as a potential early mover in developing low carbon technologies that could enable it to gain a world-leading position. Without a heavy legacy of internal combustion engine technology, the government and some industrial analysts believe that the young Chinese automobile industries will be able to concentrate their efforts on alternatives such as electric hybrid or fuel cell vehicles and leapfrog into these new technologies quicker than their western competitors. This new technology movement also enables some companies that have not previously been automobile manufacturers to take advantage of their own speciality. This possibility has already become a reality for one Chinese firm: BYD Auto that founded only in 2003. It originates from a global leading battery manufacturer, and has been selling the world's first mass produced plug-in hybrid car (the BYD F3DM) in China since December 2008.

The support from government is crucial for the success of these alternative fuel vehicles. The Chinese government lowered consumption tax in early 2009 in favour to energy efficient small engines and alternative fuel vehicles such as hybrid or all-electric cars, and aims to have 5% annual sales from hybrid or alternative fuel vehicles by 2012 (State Council 2009). These industries are also backed by measures such as R&D support, subsidies for pilots in some cities and public procurement. Universities and research institutes are already heavily involved in research projects on electric and fuel cell cars and coaches which were used in the Beijing Olympics.

Scenario 2: 111 GtC 2030

Strong innovation oriented, knowledge based high tech industry and service based economy; focus more on economic efficiency than equity; engage with global market

This scenario has a similar development path to S1 until 2020, but its overall emissions budget is nearly 50% larger than S1 following the apportionment approach of equal emissions intensity of GDP. This is an approach in favour of economic efficiency and high GDP growth – leading to the highest economic growth among the four scenarios (the economy of 2050 is 13 times larger than that of 2005) and the largest final energy demand. This larger budget also allows the scenario to include continued emissions growth for a further 10 years after the S1 peak to 2030. However, as the S2 economy includes an early transition away from heavy industries and a rapid rate of low carbon technology diffusion, the peak of emissions in 2030 is relatively low: about 35% higher than the 2005 level at 1886 MtC. TPEC is 50% higher in 2030 than in 2005. Further decarbonisation of the Chinese economy will see its carbon emissions reduced to 15% less than the 2005 level in 2050, while TPEC almost doubles. The energy intensity of the Chinese economy will also be reduced to 50% lower than 2005 level in 2020 as in S1, and to about 15% of the 2005 level in 2050. The carbon intensity of GDP will be reduced even more to just 7% of the 2005 level due to decarbonisation.

Since they are actively engaged in a globalised economy, industries in S2 are exposed to global competition but also exploit the global market for a higher contribution to the overall economy.

By 2050, industries will account for 27% of the GDP, with more than 20% from HTV, and services will account for 70% of the GDP. This is similar to the economic structure of Germany today, will a slightly lower share for industry and a higher share for agriculture. However, given the large size of GDP (50% higher than S1), the service economy is much larger than that of S1. As a result, social welfare is improved but income disparity is larger than in S1 as a result of a focus on economic efficiency and growth. The government is active in provision of services, such as healthcare, education and social support to complement the private actors delivering these services. Social and communal integration have made significant progress, but are not as far-reaching as in S1.

Energy and Power mix

In this scenario, renewable energy, especially wind and solar PV, will develop quickly as a result of close international collaboration and innovation combined with critical localisation within the domestic market. However, with TPEC 70% higher than in S1, renewable energy accounts almost the same share (32%) as in S1 in 2050, but with much more diffusion of advanced wind and solar energy. Significant shares of TPEC also come from coal (23%), oil (20%) and gas (15%), though the latter two largely rely on imports. This reflects the less constrained emission budget of S2 in comparison with S1. With strong financial and technological support in both transfer and development, the costs of renewables fall to become competitive with fossil fuels by 2020. With fast growth in both wind and solar PV, the power sector will see a quick decline in the use of coal from 80% in 2005 to a mere 35% in 2050. On-grid power generation from renewable sources will increase to 30% in 2020 and 56% in 2050, or 61% with off-grid generation. In 2050, wind, solar PV and hydro will have generation capacities of 697 GW, 818 GW and 399 GW respectively (Box 3). Wind will account for nearly a quarter of grid electricity in 2050 and even more if off-grid wind is included. Solar will also overtake hydro to contribute more than 15% of total generation, compared with 12% from hydro. Large hydro power, which is included as renewable in this scenario, yet controversial in an international context, develops less quickly than other renewable options. But it remains as the largest non-fossil energy source for power generation in China for the next few decades. It takes until 2040 for wind and solar PV to catch up and overtake hydro. Nuclear only contributes 2-3% of total power in 2050 with 40-50 GW capacity, as it is outcompeted as an unfavoured option by the development of renewable technologies. A relatively large carbon emission budget also reduce its acceptability as the benefit of carbon saving does not overweigh its potential risks. The power generation structure of S2 in 2050 is shown in Figure 18.

Power generation from coal and natural gas remain large, thanks to a larger emissions budget and economic structural change. With continuous investment in infrastructure, natural gas imports via both middle Asia and LNG ports are widely available. CCS will diffuse slower than in S1 and only diffuse gradually over time. This is because of less stringent pressure to cut emissions beyond 2020 and a large share of renewables in power generation. It is also due to concerns about the cost and the impact on the international competitiveness of Chinese economy. Therefore only one third of the coal and gas fired power plants that generate around 36% of total electricity in 2050 will be equipped with CCS. Overall, electricity generation in 2050 will be more than 6.4 times larger than in 2005. Fossil fuelled electricity, including CHP using coal and gas, will nearly triple between 2005 and 2050.

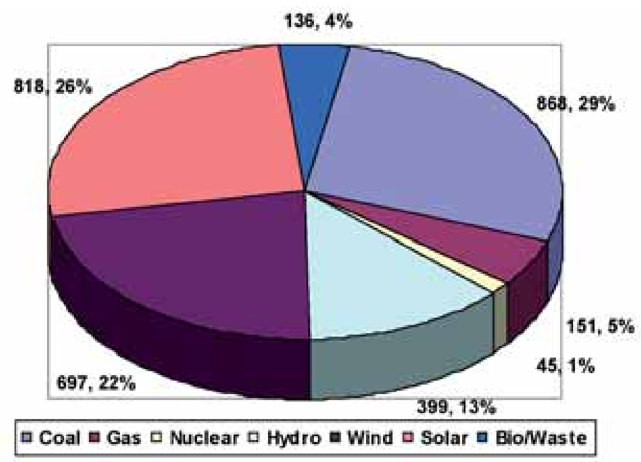


Figure 18: Power generation capacity and percentage of each source in 2050 (S2)

Box 3 China's Renewable Revolution

China is the world largest renewable electricity producer in the world (REN21 2008), with more than two thirds of the renewable electric power capacity of the EU-25 combined. However the majority of renewable electricity, 47 out of 52 GW excluding large hydro in 2006 is from small hydro. Wind only accounts for 2.6 GW compared with the 20.6 GW in Germany, then world leader in wind power. However, the situation of wind power is changing very fast in China. Just 1 year after the Chinese government released the target of wind power development in 2006 (NDRC 2007b), the 2010 target of 5 GW was met in 2007 and by 2010 wind power capacity is expected to reach more than 20 GW. Some estimate that grid connected wind power could reach 70-120 GW by 2020. Solar PV is still too expensive to be implemented in large scale in China, but the Chinese government has carried out an ambitious rural electrification program in which small or household PV solar systems are used to provide electricity access to people who would be too expensive to reach via the established grid in near future. Between 2001 and 2003, 1 million people in 1000 remote townships started using power that is largely brought to them by PV or PV/wind hybrid systems (NREL 2004). The government is planning to bring universal access to basic household electricity to every household in China by 2015, by electrifying the remaining 1-2% of households using these systems.

Behind this growing renewable electricity generation are booming wind and solar PV industries in China. China already dominates the world production and market of solar thermal water heaters, with three quarters of world's new additions in 2006 and almost 80% of global production (REN21 2008). In the fast growing wind power market, indigenous wind manufacturers accounted for more than 50% of annual capacity additions for the first time in 2007, compared with only 29% in 2005 (Li, Gao et al. 2008). Among them is Goldwind that has grown to be one of the world's top 10 wind manufacturers since it was established in 1998. Overall the wind industry in China is expected to top the world wind turbine manufacturing league by 2009 (The Climate Group 2008). Wind power is strongly supported by the government through wind concession programs and supportive feed-in tariffs but that is not the case for solar PV. The Chinese solar PV manufacturer Suntech Power founded in 2002 had already become the world third largest manufacturer by 2008. Its products are mainly exported to European and US markets where solar PV enjoys more cost competitiveness with conventional fossil fuels due to lucrative government subsidies. Following a similar strategy, many Chinese solar PV companies developed quickly over the last few years. In 2003 China only possessed 1% of global solar PV production, while in 2007 this figure has jumped to over 18% (The Climate Group 2008). Overall, China topped in global renewable energy investment with Germany in 2006 at $7 billion each and came second after Germany in 2007 at $12 billion.

The Chinese leadership now regards green industries, especially the new renewable energy industries, as a key area in which China could gain a global leading position when compared to its position in other industries. Due to this ambition and the economic policies to counteract the effects of the global recession in China, China's renewable energy industries are looking promising. But to realise the very large expansion of renewable energy depicted by S2, there are more obstacles than just technology and capital to be overcome.

Industry and services sectors

China's industrial structure in this scenario will be very different to now by 2020. Engaged with a globalised economy, industry will respond actively to demand from both domestic and international markets, but in a more balanced manner than China's current export-led economy. Combined with the promotion of science and technological innovation, HTV industries develop much quicker than the energy intensive and conventional industries. This leads Chinese industry to transit quickly from the dominance of traditional and heavy industries to highly innovative, high technology industries. Although its contribution to GDP just increases from 9% in 2005 to 20% in 2050, the size of HTV industry increases more than 30 times over the 45 years. This compares to only 79% and 179% increase in heavy and conventional industries, as they are already significantly large in China's current industrial structure. Industry overall will account for 27% of GDP in 2050, with over 75% of this coming from HTV industries (see Figure 19). Industries, like biochemical, electronic, auto and high precision machinery tools, will keep evolving with new innovation and technologies, and act as engine of overall economic growth. Energy efficiency improvements and new materials use have helped to reduce the environmental impacts of heavy and conventional industries. Services account for 70% of the overall economy, a lower proportion than in S1 but much larger in size. Apart from other services, energy management services prevail from primary energy providers to end users, as required by regulations. The government is a significant player in the energy system, via both regulation and R&D support, especially for long term investment in some advanced technologies. Agriculture has a lower

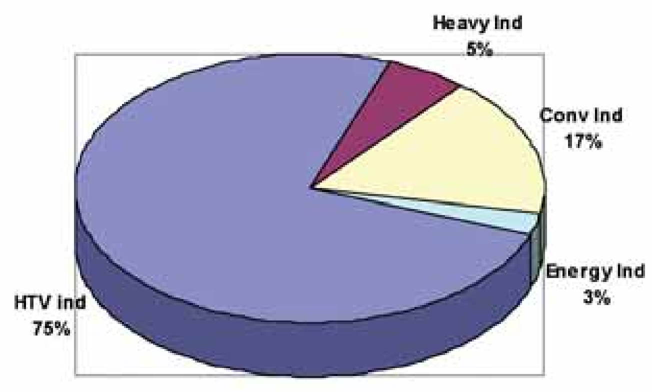


Figure 19: Industrial GVA contributions of different industries in 2050 in S2

share in the economy in S2, partly because the international market will play a larger role, but also because a greater variety of foods than domestic production can provide will be needed in the diet of households with a larger disposable income than in S1.

Households and personal transport

In both transport and heating, fossil fuels remain important energy sources. Natural gas is prioritised for household use, including off-grid CHP at communal level. Nearly than three quarters of natural gas is used for household use in 2050, including cooking, electricity and heating from CHP. But this figure has seen a decline from an even higher level due to energy efficiency gains and larger deployment of renewable technologies in the households. Overall 16% of household energy use in 2050 is met by natural gas, after grid electricity (39%) and renewables (35%). Similarly, nearly half of total oil consumption is for railways and road transport in 2050. When oil use in aviation and shipping are included, this figures increases to over 80%. Oil plays a much larger role in railway and road transport than in S1, and fuels half of the private vehicle use, 40% of railway and public road transport use.

The population is concentrated in quite a few metropolitan cities and large number of small cities. With a highly developed service sector, these metropolitan cities are dynamic centres of economic and social activities. Population density is medium and people live in moderately sized but very efficient houses or flats. Overall emissions from households and private transport increase rapidly to 2030 before reaching a plateau afterwards. Household energy consumption and its associated carbon emissions increase largely due to higher income and living standards. This will be partially offset by improved efficiency brought about by new, innovative technology applications diffused through the application of stronger standards. Housing will be built to a much higher level of energy and material efficiency than today. Micro generation and passive energy design will provide a significant share of household energy consumption, yet the centralised supply system will still be very important, particularly through grid electricity. In cities, comprehensive and efficient public transport provides a primary means of transport for commuters. Although private transport is still an important and widely available means of travelling outside of cities, vehicle and fuel technologies have made it more environmental friendly. After 2030, more radical transport technologies and infrastructures such as hydrogen fuel cells and advanced biofuels will cut emissions substantially. Due to a higher demand for mobility, international aviation and shipping will also increase quickly, which are both mainly fuelled by oil. Environmental education and awareness-raising will lead people to choose more green options. The impact of this is initially offset by consumption increases, but becomes significant after 2030.

Scenario 3: 90 GtC 2020

Global and domestic driven economy with service basis; manufacturing and heavy industry persist; people focuses on welfare and disparity reduction;

This is an economy that is globalised, but with significant focus on domestic investment and development. The 90GtC cumulative emission budget is at the median the four scenarios. However with slow economic structural change, it is a more challenging task to stay within this budget than it is for the lower budget in S1. The economic growth rate in this scenario is lower than S2, because of this renewed local focus and a continued reliance on conventional manufacturing industries. Similar to S1, government and society focus on welfare coverage and providing equal opportunity of development and access to resources. It is stable and equal but less dynamic due less innovation. Social welfare is given more priority than economic expansion, resulting in a strong social welfare system supported by both public and private sectors. The economy grows to over 10 times as large as in 2005, with the most contribution, 78% of GDP coming from the service sector. Industry will account for only 19% of the total economy in 2050, the lowest of the four scenarios. The contribution from HTV industries will not be much larger than the conventional and heavy industries which mainly persist to supply domestic needs. The economy and industrial structure of S3 in 2050 is close to that of the United States.

China's carbon emissions will peak at around 2020 and will have to undertake a quick reduction of 4-5% per annum to remain within a challenging emissions budget. Carbon emissions will be 70% higher than the 2005 level when they peak in 2020, and then will fall to only 40% of the 2005 level by 2050. Energy intensity will be reduced to only 16% of the 2005 level in 2050, with carbon intensity reduced to only 4% of the 2005 level. Innovations in this scenario tend to be incremental rather than radical. Government is not very efficient in providing welfare. Efforts to promote adaptation to climate change are high on the agenda and form an important part of broader social services provided to communities.

Energy and Power mix

A unique feature of the energy and power mix in this scenario is the relatively large role that nuclear power plays. With less technology advances and lower level of international collaboration, renewable energy sources like wind and solar will take more time to become technologically and economically viable whereas small hydro and biomass have limited capacities to support China's energy needs. TPEC will peak in 2020 at about 90% higher than 2005 level and gradually decline to about 75% higher, and plateau afterwards. Coal remains as the most important energy source, accounting for 31% of TPEC in 2050, followed by renewables, oil and nuclear. This scenario has a quite balanced mix among the major energy sources, with the least of them contributing more than 10%.

Nuclear becomes a favourable choice for medium term emissions reductions from the power sector – and fits with a continuation of a centralised model of energy production and a desire to reduce the dominance of coal. Within the logic of this scenario, it also carries some particular advantages over renewables in the early decades by providing a constant base load to the manufacturing industries (Box 4). The quickest nuclear power expansion in history so far was seen in the 1980s during France's State-led programme of nuclear power. 45 GW of nuclear power was installed between 1980 and 1989 - 9 GW alone in 1981[9]. Due to the

[9] World Nuclear Association, latest updated in April 2009.

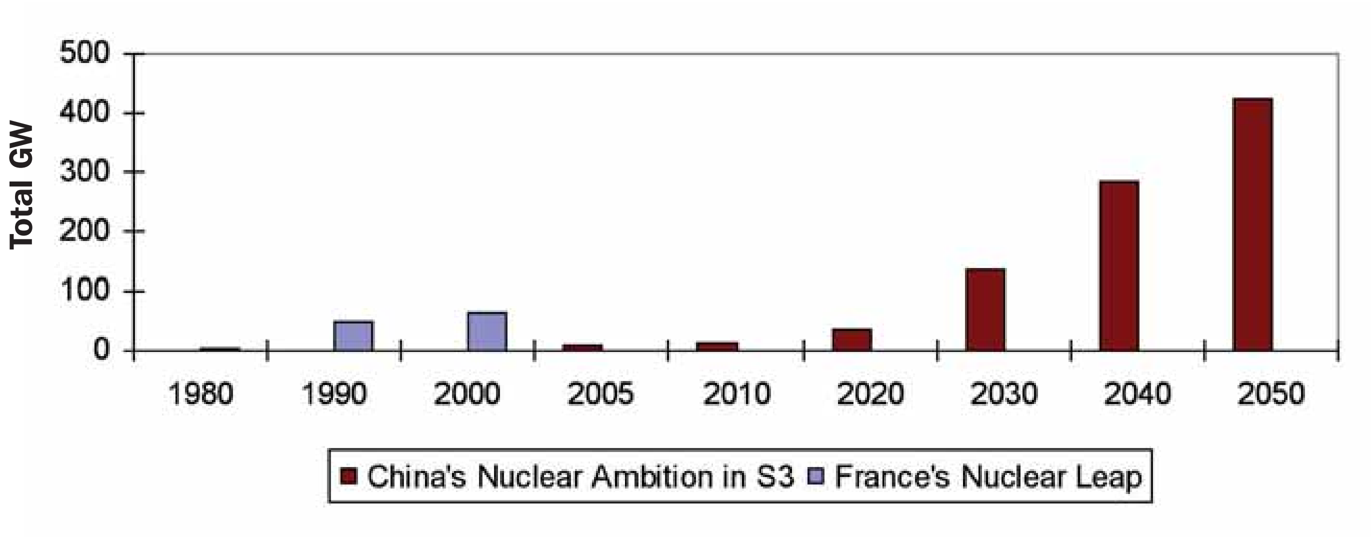


Figure 20: The nuclear power take-off in S3

extraordinary ambition of nuclear power expansion in this scenario, China will have to embark on a nuclear upscaling that is 2 to 3 times faster than the fastest rate that France achieved in the 1980s. China will add nearly 100 GW of nuclear capacity in S3 between 2020 and 2030, and nearly 150 GW in each subsequent decade to 2050. The total generating capacity will reach 423 GW in 2050, 7 times as large as the current French fleet, as shown in Figure 20. Even with this grand investment in nuclear power, it will only account for 26% of total electricity generation in 2050, and about 12% of TPEC. Fossil fuels (mainly coal) and renewable energy will contribute 37% of power generation each. Cleaner coal technology is therefore given a high priority to enable the quick short term emissions reductions around 2020, including ultra-supercritical and integrated gasification combined cycle, or IGCC power plants. CCS is urgent and mandatory from 2020 – and is rolled out for older power plants when feasible after that date. 30% of coal power plants will be equipped with CCS in 2030.
This will increase to over 80% in 2050.

China signed a contract in March 2007 with Westinghouse to introduce four units of AP1000 reactors which marks the start of a new round of nuclear power expansion (see Box 4). But this design, as well as another candidate, the EPR from Areva in France, has not been practically proved anywhere in the world. Therefore it is associated with significant economic and financial risks. This has already been shown by the delays and cost over-runs at the world's first EPR project in Finland.

Oil remains important for transport in the short and medium terms, but is replaced as the need to reduce carbon emissions quickly becomes apparent after 2020. Renewable energy develops slowly. Small hydro and some biomass are deployed in areas where these resources are widely available – particularly in rural areas. Wind and solar PV only have small shares by 2030 for technological and cost reasons. They will take longer to upscale, accounting for 11 and 4% of power generation respectively in 2050, with 330 GW and 150 GW installed. Some progress is made in micro-generation to generate electricity and heat for households,

Box 4 Nuclear Power Program in China

China's nuclear power has been developing slowly for almost 10 years since the first nuclear power plants was built in 1993. It has started picking up speed since 2003 after severe power shortages in China in early 2000 together with a desire to reduce dependence on coal.

As China revised its nuclear power strategy much quicker development of nuclear power is now expected. The capacity increased from 2.1 GW in 2001 to 10.8 GW in 2008, with 11 GW under construction and a further 15 GW approved. Currently in China there are 11 nuclear power reactors in commercial operation, 7 under construction and 10 about to start construction (WNA 2009). The Chinese government made plan in 2006 to have 40 GW of nuclear power by 2020 but it is expected to be raised to at least 60 GW in 2020 and 120 to 160 GW in 2030.

China seeks to obtain and develop state of art nuclear power technology by "Sino-foreign cooperation, in order to master international advanced technology on nuclear power and develop a Chinese third-generation large PWR (Pressurized Water Reactor)" (NDRC 2007d). Based on this strategy, technology transfer became a major factor in a 22 months long bidding process for the 4-8 GW nuclear plants in Sanmen and Yangjiang. The Westinghouse AP1000 reactor eventually won with a promise to transfer the technology over to Chinese partners after the fist 4 units (WNA 2009). In November 2007, a similar agreement was reached with Areva for 2 EPR units in Taishan with full technology transfer. At the same time, the so called CPR-1000 or "improved Chinese PWR" derived from Areva's technology will be widely used for domestic nuclear plants using indigenous technology. China expects to gain state of art "third generation" nuclear power technology for further development through these collaborations, but eyes on fast breeder reactors in the long term (NDRC 2007d). China aims to become self-sufficient in reactor design and construction, as well as other aspects of the fuel cycle.

However, half of China's current uranium need is met by import, from Kazakhstan, Russia, Namibia and Australia. Although China's uranium reserve is theoretically sufficient for its short term nuclear program, the ores are low grade by international standards. China has already started to acquire uranium resources internationally. With the nuclear expansion depicted in this scenario, China will rely heavily on imported uranium to fuel the nuclear power fleet which will have important international implications (see section 6 of this report for more analysis).

but this is only supplementary to the dominant centralised mode of provision. Cogeneration on site for industry prevails to reduce energy loss in transformation and transmission.

Industry and services sectors

In this scenario, Chinese industry will respond to a combination of domestic and international markets – with some rebalancing in evidence. Exports will plateau by 2015 and start declining after losing cost competitiveness. But industry will still be boosted by domestic demand from ongoing economic growth. The industrial sector will include a fair share of high technology industries, but conventional manufacturing industry will remain equally important, unlike in S1 and S2. Incremental energy efficiency and material improvements reduce the overall carbon and energy intensity of industry but relatively slowly. The service sector has grown significantly from 42% in 2005, to dominate the economy with a contribution of around 78% of total GDP. Government is an active service provider alongside the private sector. As a result, the economy is in general not reliant on either exports or industry. Agriculture only accounts for 2.7% of GDP in 2050, as it remains low value-added and labour intensive in the economy.

Households and personal transport

Energy demand from households and the transport system increases moderately in this scenario compared with S2. This is partly due to a less affluent society and a large public transport system, but is somehow offset by the large house size and more dispersed population living in a number of closely linked medium-sized cities (like Suzhou, Changzhou, Yanghzou and Wuxi along the Yangtze River delta). Population density in these cities is lower and people prefer to have more space with fewer crowds.

Energy efficiency improvements will contribute to emission reductions but less so than in the first two scenarios. Both old and new buildings are required to comply with stringent energy efficiency standards and there is significant use of natural lighting and renewable energy when possible. Solar heating is important for hot water and heating, but there are also important contributions from gas and electricity. However, due to low energy efficiency and slower development of renewable technologies, almost half of the energy in households is from grid electricity. Micro- and decentralised energy generation is well supported but is constrained by slow diffusion – and there is a general preference for centralised solutions.

Private car ownership will experience a rapid increase in the first decade of this scenario but more stringent economic and policy incentives manage to slow down this trend. People increasingly use more public transport particularly in cities, and private transport use declines as a result. Advanced biofuel technology and electric cars will reduce oil demand to some extent, but neither of them has made a deep penetration in private transport, leaving half of it still fuelled by oil in 2050. Even less alternative fuels are used in shipping and aviation. This leads to nearly 50% of total emissions in 2050 coming from transportation alone, mainly due to oil use. Households only account for 15% due to their reliance on decarbonised grid electricity. Environmental education and awareness will make people much more inclined to 'green' consumption. Behaviour change becomes an important feature and source of carbon emissions reduction after 2020.

Scenario 4: 111 GtC 2030

Strong conventional manufacturing industry in globalised economy; susceptible to external shocks; strong focus on growth; divided society.

The economy in this scenario is a strongly globalised one with significant contribution from heavy and conventional manufacturing industries. GDP growth is therefore more uncertain as it is susceptible to changes in export market and faces severe constraints in energy and resources availability due to the huge demand of manufacturing industries. The economy size in 2050 is the smallest among the four scenarios, just over 8 times of the 2005 level while the TPEC is the highest of the four scenarios. Even with the largest cumulative emissions budget as S2, the late transition of economic structure and major persistence of manufacturing industries make it the most challenging scenario, which requires halving its emissions in 10 year after its emissions peak in 2030. The society is less innovative than S2 and the pursuit of economic growth leads to large investment in deepening conventional and heavy industrialisation in the near term. But with continuous incremental innovations and improvement the industry sector is more energy and resource efficient than it is now. Both industry and service sectors have a large share of the economy while agriculture is less developed because of the competition from imports. Annual carbon emissions keep rising after 2020, albeit a slower rate to 2030 due to gradual structural changes. The peak emission in 2030 will be more than 80% higher than 2005 level, and then it has to be slashed to half in 10 years time, mainly through a massive CCS roll out with stringent energy efficiency improvement, and inevitably some decline in the industry sector. By 2050, further emissions cut will be needed to reach only 30% from the peak in 2030, or 55% of the 2005 level.

Energy intensity in S4 is the highest of the four scenarios due to its economy structure, about 24% of the 2005 level in 2050, and carbon intensity is reduced to 7% of the 2005 level. Industry accounts for 33% of total economy even in 2050, a share higher than most OECD countries today. Social welfare system is established but not very comprehensive due to weak support from private sectors. A rich and powerful central government provides large scale top-down social welfare care. Technological and science innovations are mainly promoted by government and large industries at their initial stages, but the diffusion and deployment are much slower. China will have a strong industrialised economy and will remain a major trade power in the manufacturing economy. As economy grows, pressure on poverty eradication is to some extent alleviated but the income disparity increases which in turn increases the concern of instability in the society.

Energy and Power mix

Energy demand in this scenario is the largest among the four in 2050. The TPEC has more than doubled by 2030 from the 2005 level and declines to just less than double of the 2005 level in 2050. Compared with S3, fossil fuels make up a large share in the energy mix due to better access to oil and natural gas from international market. Nuclear and biomass are reduced to smaller share. Renewables will take a long time to mature and deploy, but will steadily increase it share in the TPEC and keep replacing traditional biomass with more advanced renewable alternatives. Renewable energy such as wind and solar PV will benefit from international collaboration and joint R&DDD, as well as the manufacturing power of the economy. Hence they could roll out quickly once they are commercialised and become economic competitive.

Coal fired power plants remains significant in the power sector, contributing more than 40% of electricity generation in 2050. It will climb to its peak generation capacity at 1200 GW in 2030 and then reduce to about 1100 GW in 2050. In order to comply with emissions budget, CCS has to be rolled out quickly in fossil fired power plants, including natural gas, from almost none in 2030 to 90% in 2050, as shown in Figure 21. Before 2030, efforts are focused on more efficient technologies such as ultra-supercritical boilers and IGCC. Assuming the technological and economic uncertainty of CCS could be solved by 2030, building new fossil fuelled power plants as capture ready[10] before then would be necessary to make the later fast CCS roll out possible.

Adoption of CCS is initially low due to its cost and efficiency penalty, but would increase quickly as it becomes apparently critical to achieve required emissions cuts. Widespread implementation therefore follows from 2030 with an ambitious programme of new build and retrofitting. Natural gas power plants will also be prioritised in power sector after more natural gas becomes available from both domestic reserves and international markets not only for its superior environmental and efficiency performances, but also its special value in balancing the intermittency of renewable power generation. There will be 130-160 GW of natural gas power plants in 2050, more than ten times growth from now, but still subordinate to coal.

Box 5 Carbon Capture and Storage

Carbon capture and Storage (CCS) is now considered technically feasible at commercial scale (Gibbins and Chalmers 2008) though the world's complete CCS demonstration was only launched in September 2008 in north Germany. The EU promised to have 12 CCS flagship demonstration project by 2015 and it also signed an EU-China NZEC agreement at the EU-China Summit under the UK's presidency of the EU in September 2005 to demonstrate advanced, near zero emissions coal technology through CCS in China by 2020. As part of it, The UK-China NZEC initiative is now in its first phase to explore options for demonstration and building capacity for CCS in China before the first demonstration plant in China by 2014. Within the UK, a bidding competition is going on for a government funded 300-400MW demonstration project that is also due to be open by 2014. Despite the government funding withdrawn in January 2008 the US flagship project Futuregen Alliance continued move forward and is now expected to be revived under the new Obama administration.

There is no scientific breakthrough needed for the CCS, as it has already been used in petroleum industry at smaller scale. There are three main technologies, oxyfuel, which involves burning fuel in almost pure oxygen which is then relatively easier to separate CO_2; post-combustion, which has flue wet scrubbed

[10] Capture ready is a design concept enabling fossil fuel plants to be retrofitted more economically with carbon dioxide capture and storage (CCS) technologies. Capture-Ready should not be restricted to capture alone in the sense that a CCS project will need to be integrated across capture, transport and storage … the concept of Capture Ready should ideally incorporate plant sitting to allow as much as possible of the captured CO2 to be transported to the storage site in order to lower the total cost of the whole CCS process. Source: CaptureReady.com

with aqueous amine solutions from power station chimneys and pre-combustion capture that involves the removal of CO_2 from the fuel prior to combustion. The CCS project in Germany used oxyfuel while it is likely that the UK demonstration will use post-combustion technology. While the technologies are yet to prove themselves, there are also critical aspects of CCS that need to be addressed, such as reliability of geologic storage and monitoring potential leakage, to facilitate large scale deployment.

China is seen as a critical player and potential leader in CCS deployment, due to its large capacity in coal fired power plants and strong knowledge base in coal technology, and the government's ambition of leading clean coal and low carbon technologies. However, the inherent efficiency penalty means coal fire power plant will need either economic incentives or legal and regulatory requirements or both to be motivated to adopt CCS. But this will not be possible without a strong commitment, both financial and technological, to CCS from the developed country under the post-2012 climate agreement that is expected to be agreed in Copenhagen in December 2009.

Similar to scenario 3, this scenario will see a slower roll out of advanced low carbon energy technologies due to a weaker innovative capacity. Renewables other than hydro will develop slower than in S2 due to inadequate science and technology advances. More advanced renewables like solar PV and fuel cell will only be widely deployed after 2030 or even later. Eventual wind will grow to account for 17% of total generation and 575 GW of generation capacity, followed by 10% from hydro and 8% from the solar PV. The choice of nuclear power will be supported by the electricity needs in large industries and hence contribute to more than 10% of total electricity generation in 2050. It will reach nearly 200 GW of generating capacity, much higher than both S1 and S2. Decentralised power and heat generation will

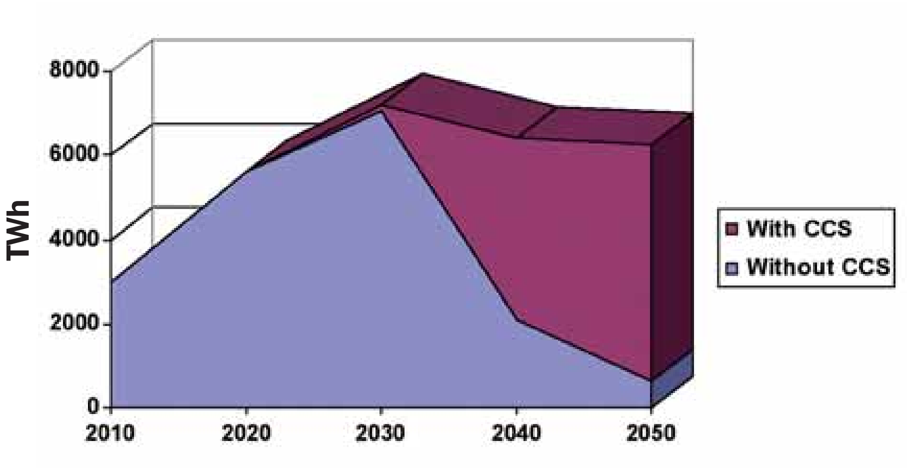


Figure 21: The CCS penetration in fossil fuel power generation in S4

develop gradually but are constrained by cost and lack of institutional support from a centralised energy system. Solar water heaters would be the main form of micro renewable before 2015, with significant use of CHP powered by both biomass and natural gas after 2015. Household PV will only become a competitive choice after 2020 with strong government support.

Industry and services sectors

Driven by the global market, Chinese economy in S4 is equipped with strong manufacturing capacity. The Chinese industry will maintain a high proportion of heavy and conventional manufacturing – with some shifts up the value chain to more technology intensive industries. As a result, heavy, conventional and HTV industries are broadly taking the same share in the industries' overall 33% strong GDP contribution. By 2050, heavy and conventional industries will grow to between 4-5 times as large as the size in 2005 while HTV industry will increase more than 12 times. This is a much smaller growth compared with more than 30 times in the S2. Despite being a major trade and manufacturing power of the global economy, lack of radical innovation and technology breakthrough constrains the ability of Chinese enterprises to become a world leader in technologies innovations and new products, hence prevents them from the most hefty profits from trade. China will become further integrated into the international patterns of production and markets. Promotion of science and technology innovation has made a significant contribution to the emissions reduction but has failed to reshape the industrial structure quickly. Energy efficiency and supply chain changes also helped to realise large, incremental emissions reductions, particularly in the conventional and heavy industries (Box 6). The service sector will constitute 64% of the economy in 2050 from 42% in today, while agriculture makes up for 3%. Welfare is provided through state run agencies to minimise the adverse impacts of income disparity in society, but their performances are held back by bureaucratic administration and lack of incentive to improve efficiency compared with their expensive and dynamic private competitors in niche market, which in return also fuels disparity and a stronger pursuit within the general public for economic growth.

Box 6 1000 Enterprises Program

The Chinese government launched the 1000 enterprises program in April 2006 to improve the most energy intensive industrial users as a key effort to conservation energy consumption and reduce energy intensity in the 11th Five-Year plan. The 1000 enterprises (998 in exact number) cover 9 industrial sectors consisting of, in the order of energy use, iron and steel, power, chemicals, petroleum and petrochemicals, coal, non-ferrous metal, construction material, paper and textile. The first 4 sectors account for 82% of the total energy demand. Overall, the 1000 enterprises represent almost half of total industrial energy consumption and one third of China's total energy consumption. The target is to reduce annual energy demand by 100 Mtce from the baseline by 2010. If it was met, this program would represent an annual reduction of 260 million tonnes (Mt) of CO_2.

International technological and financial aids were provided to the enterprises from both United Nations and the EU, and agreements were signed among central government, local governments and the enterprises to stipulate the individual goals of each province and enterprise. The performance of energy saving was monitored and supervised and will be taken account in assessment of the leaderships of both local governments and enterprises. An initial review in 2007 showed that the 1000 enterprise program is well on track and could even achieve 50% more saving than planned in 2010, which would result in an annual CO2 emissions reduction equivalent the total emissions of South Korea (Price, Wang et al. 2008). Yet the Chinese industrial system is very complex and the fact that 20 Mtce energy saving was achieved in 2006 just through a quick design and implementation without fully implementing the best practices reveals the huge potential of energy efficiency improvement in China's industries.

Household and personal transport

People in this scenario are constantly attracted to a few supersize mega cities where economic growth and living standard is very high. The income disparity between urban and rural area is therefore large and causes constant migration flow from rural area to urban cities. This results in a high population density and small living area in those mega cities, which in return reduces the energy consumption per capita.

Household consumption and transportation will increase quickly in this scenario due to the increase in household income and living standards combined with slow diffusion of low carbon alternatives. Offsetting effect from efficiency improvements is limited too in the early decades. However, the situation will change later and after 2030, when stringent energy efficiency improvements and energy decarbonisation will help the emission from household and transport sectors to decline after 2030, a major contribution to the ambitious emission reduction required after 2030. Household and transport sectors will become the largest sources of emissions before 2040. Construction codes for housing place significant emphasis on energy and material efficiency such as passive energy savings but less in integrating renewable energy. As a result, micro generation only manages to provide a small share of household energy consumption and almost half of the household energy demand is met through grid electricity. In the rural area, advanced biomass and biogas together with micro generation provide significant energy needs.

Public transport is well established in most cities, with very intensive use in those mega cities. But private transport is also highly relied upon by regular commuters, especially between regions. There is less demand side reduction in private road transport compared with other scenarios. This is somehow related to the social preference for 'individual' transport solutions to 'public' ones. Low carbon vehicle and fuel technologies have made some significant progress globally but higher cost prevents them from becoming a popular choice until after 2020. Biofuels and mixed fuel vehicles become more important since then. But overall Oil-based transport remains important, and do not face significant competition from alternative fuel transport until 2030. More advanced improvements such as hydrogen powered fuel cells are not widely available in the market even in 2050. International aviation and shipping demand both increase very fast in response to a high demand for mobility and trade in a globalised economy. In combination, aviation and shipping will account for 40% of energy use in transportation, same as private road. As a result, 57% of China's total carbon emission in 2050 will come from transportation alone, and oil, across its use in all sectors, will account for 60% of the total emission as it is difficult to be decarbonised. Environmental education and awareness-raising have managed to encourage some people to choose more green consumptions but it takes time to diffuse into wider community.

6.Thinking beyond carbon

Whilst the main aim of this report is to explore future energy pathways for China that comply with a given carbon budget, it is important that the analysis is not too one-dimensional. There are two main reasons to think beyond carbon in relation to our scenarios. First, other greenhouse gases such as methane and nitrous oxide are also responsible for anthropogenic climate change. Second, China's future energy system will need to contribute a large number of other policy and social goals as well as climate change mitigation. Issues such as local air pollution, access to energy services and energy security are important drivers of energy policies in China. It is increasingly recognised that sustainable energy transitions can only be fully assessed if these additional drivers are taken into account alongside the imperative to tackle climate change (e.g. Kowalski, Stagl et al. 2009).

The extent to which the scenarios in this report will mitigate China's emissions of other greenhouse gases is beyond the scope of this report. From a methodological point of view, this is not problematic because the global carbon budget that has been used to derive cumulative emissions budgets for China is for carbon only. Alongside this are assumptions about the necessary trajectories of emissions of other greenhouse gases. However, the practical development and implementation of low carbon development strategies for China will need to include the abatement of these other greenhouse gases.

Turning to the second rationale for a broader assessment of the scenarios, it is desirable to devote some attention to the implications of the scenarios for other dimensions of sustainability. These include the demand for natural resources, the implications for other forms of pollution (e.g. for local air quality), the implications for poverty alleviation and equity, and the extent to which pursuing the pathways identified in the scenarios would be compatible with energy security. This project has not conducted a comprehensive assessment of all of these dimensions. This section focuses on two sets of issues which have been chosen in consultation with our expert interviewees.

The section first assesses the implications of the scenarios for energy resources (both fossil and non-fossil). It then discusses some of the energy security challenges that are highlighted by the scenarios. Within the analysis of these two sets of issues, the section also considers some of the additional dimensions of sustainability when they are thought likely to be particularly relevant and important.

Energy resources

Fossil fuel resources

Whilst the use of fossil fuels in modern energy systems is a key cause of anthropogenic climate change, the Tyndall Centre scenarios show that radical low carbon development pathways do not necessarily mean the end of fossil fuel use. Like most other countries, China is heavily reliant on fossil fuels for electricity generation, industry and heating. As noted earlier in this report, the use of coal is pervasive and accounts for two thirds of China's primary energy needs.

In all of the scenarios described in this report, the demand for coal in 2050 is lower than the demand in 2005. Though in all cases, demand has continued to rise before declining. By contrast, the demand for oil and natural gas in 2050 is much higher than in 2005. Economic growth and the associated increases in energy demand in these scenarios mean that the use of these fossil fuels rises despite significant substitution for oil in transport.

One important implication of this continued fossil fuel demand – including significant growth in many cases – is the continued depletion of global reserves. In the case of oil, there is widespread concern that this will lead to high prices and that sufficient investment may not be made to ensure adequate global supplies (IEA 2008a). More fundamentally, there are increasing claims that oil production will peak in the near future, though such a diagnosis is far from universal amongst oil analysts.

Table 2 illustrates how the scenarios would contribute to global fossil fuel depletion, and compares cumulative demand within China to current estimates of fossil fuel reserves. It clearly shows that demand for oil and gas will exceed China's own reserves by a large margin unless there are significant new discoveries. China is already a net oil importer, a position that would not change within these scenarios. Cumulative demand reaches well over 10% of current global reserves in three of the scenarios. Natural gas demand in China has been relatively low due to the lack of availability of significant reserves and – more recently – high international prices. Within the scenarios, gas demand expands to at least several times the current level. Cumulative demand reaches up almost 10% of global reserves.

For coal, the picture is rather different. China's vast coal reserves mean that in principle, cumulative demand could be met domestically. This is unlikely in practice due to economic factors (imported coal will be cheaper in some cases) and the need to burn low sulphur coal that minimises acid rain pollution.

	S1	S2	S3	S4
Coal Demand (2005-2050)	40,314	47,669	59,721	67,800
Coal Reserves				
- China	80,070			
- Global	592,649			
Oil Demand (2005-2050)	15,100	24,040	19,987	25,504
Oil Reserves				
- China	2,100			
- Global	168,600			
Gas Demand (2005-2050)	7,543	13,523	10,203	14,677
Gas Reserves				
- China	1,692			
- Global	159,624			

Table 2: Cumulative demand for fossil fuels and fossil fuel reserves (Mtoe)

The impacts of this level of demand for fossil fuels are hard to predict. Reserves figures such as those quoted in the Table are not fixed – they will evolve as a result of changes in prices and technology. Accessing these reserves will also be subject to political factors and constraints and investment in the extractive industries. All of these factors could significantly expand or reduce reserves figures – and the proportion of reserves that are economically recoverable. However, given the level of demand for fossil fuels in China within the scenarios, the economic risks of price volatility and the potential risks of disruptions to supply could be high. Further discussion of these risks is provided in the next sub-section.

A further implication of this continued use of fossil fuels for China's natural resources is important to highlight here. To allow this high level of consumption whilst remaining within the overall carbon budget, the Tyndall scenarios require a significant amount of carbon capture and storage to be deployed – particularly on coal fired power plants. This, in turn, means that adequate CO_2 storage capacity should be available in depleted hydrocarbon fields or in alternative geological formations such as saline aquifers. Between 2005 and 2050, the cumulative storage of CO_2 within the scenarios ranges from a minimum of 1277 MtC in S2 to a maximum of 5753 MtC for S4.

A number of assessments of China's CO_2 storage capacity have been carried out. As with many such estimates, they are subject to large amounts of uncertainty. One recent estimate for China gives an overall theoretical storage capacity figure of 3088 gigatonnes of CO_2 (840 GtC) (Li, Wei et al. 2009). 99% of this capacity is in saline formations. Of course, the storage capacity that can be practically and economically used is likely to be much smaller than this figure. Nevertheless, when compared to the cumulative CO_2 storage requirements of the scenarios, there appears to be ample capacity available. However, there are two important caveats to this. First, there is a need for more detailed assessments of China's storage capacity which consider the geography of sources and sinks for CO_2. The likely storage sites are not necessarily close to locations where coal-fired power plants will be located. For example, the largest potential storage reservoir is the Tarim Basin which is in the remote north-western region of China. Second, there is a need to get better estimates – particularly of capacity in saline aquifers. Unlike depleted hydrocarbon fields, many aquifers have not been investigated in detail before. For both these reasons, it is welcome that more detailed assessments are now being carried out – for example the assessment of northern China within the NZEC (near zero emissions from coal) project financed by the European Union.

Nuclear power and uranium resources

The Tyndall scenarios include different levels of nuclear power deployment by 2050: ranging from 45GW in S2 to 423GW in S3. Deployment at the upper end of this range exceeds the current level of global cumulative capacity, which is around 360GW (Zittel and Schindler 2006). In 2005, this global nuclear capacity consumed 67 kilotonnes (kt) of uranium. If the efficiency of future Chinese reactors remains the same as the current global average, the demand for uranium within China will range from 8-79kt per year. Of course, uranium demand for China's nuclear reactors in 2050 could be lower than these figures – for example due to efficiency improvements and/or the deployment of fast breeder reactors.

According to the OECD Nuclear Energy Agency, global uranium resources that are 'reasonably assured' amount to some 3300 kt (OECD

2006). In addition, there are thought to be up to 11,000 kt of resources, but these are much less certain – and are classified as inferred or undiscovered. As will fossil fuel resources, the actual size of these resources is a function of economic and technology as well as geology. Not all of the 3300kt of reasonably assured resources are economic at current prices (around $40/kg).

The cumulative demand for uranium between 2005 and 2050 from China's reactors is approximately 300-1300 kt. Again, this assumes no improvement in the current global average efficiency of uranium use or the deployment of fast breeder reactors. However, the upper end of this range represents a significant proportion of 'reasonably assured' global reserves. Even if the rest of the world also expands the use of nuclear power during this period, this does not necessarily mean that there will be a fundamental resource constraint. Technologies for mining uranium could improve significantly, exploration could identify new reserves (currently in the 'undiscovered' category), and the use of uranium could become much more efficient. However, there could be significant impacts on uranium prices if capacity scales up as outlined in the most ambitious scenario.

Renewable energy resources

The deployment of renewable energy for electricity production, transport fuels and heating rises dramatically in the Tyndall Centre scenarios. Renewable energy currently plays a relatively small role in the Chinese energy system. The mixes of technologies described earlier in this report for each scenario are illustrative, and are designed to give one set of possible pathways for renewables deployment in China. In these illustrations, a particular emphasis has been placed on wind, solar, hydro, biomass and biofuel technologies. It is possible that other renewables could also make a contribution to low carbon energy production in China over the coming decades. For example, China has a long coastline which opens up potential for wave and tidal technologies.

Within many of the renewable technologies that have been emphasised here, there are a range of potential variants. For example, solar electricity generation can be achieved by solar photovoltaic panels or solar concentrators which generate steam. A full discussion of all of these variants and their resource implications is beyond the scope of this report. Therefore this section sets out some examples to provide insights into some of the potential implications of deploying these technologies on a large scale.

China's exploitable wind energy potential was estimated recently at 700-1200GW (Li and Gao 2007). This overall range is lower than that from some previous studies because it has taken into account geographical and practical constraints to deployment. The majority of this potential (600-1000GW) is onshore, whilst an additional 100-200GW could be deployed in relatively shallow water offshore. The geographical distribution of this potential is not uniform. Wind densities in coastal provinces and northern provinces are significantly higher than in those inland provinces further south.

Our scenarios include the development of a large proportion of this potential for wind power by 2050. Cumulative deployment by 2050 within these scenarios ranges from 397GW in S1 to 738GW in S4. This represents large and sustained rates of growth from China's installed capacity at the end of 2008 (around 13GW). It also means that China could have up to eight times more wind power installed in 2050 than the world has now. It goes without saying that the achievement of these installed capacities by 2050 will be challenging in several ways. The implications for land use, electricity grid operation and capital investment will be very significant. However, it is also important to note that the trajectory of wind power deployment within our scenarios is in line with other assessments. For example, the Global Wind Energy Council's most recent scenarios include 49-450GW of wind power deployment in China by 2030 (GWEC 2008). The cumulative deployment within the Tyndall Centre scenarios is 151-367GW by 2030.

The contribution of solar photovoltaics (solar PV) to the scenarios is also very large. By 2050, deployment within the scenarios ranges from 242GW in S3 to 818GW in S2. If this capacity were installed as small installations of several kW in homes, offices and commercial buildings, tens of millions of these installations would be required across China. However, it is possible that larger centralised arrays of solar PV capacity could form a large part of this total, particularly if the promise of lower cost thin film technology is realised. For example, Pacific Gas and Electric – a utility in California – has recently agreed to buy power from two solar PV plants with a combined capacity of 800MW (Wald 2008). Several hundred of these plants would still be required to reach the capacities included in the Tyndall Centre scenarios. The land use implications are not trivial either. The 800MW of capacity for Pacific Gas and Electric will cover 12.5 square miles. Scaling up to 800GW (the largest capacity of solar PV within the Tyndall Centre scenarios) would require 12,500 square miles of land. Whilst there are suitable desert areas in China that could be used in principle, implementation would clearly be very challenging.

The use of biomass and biofuels within the scenarios is extensive. Whilst biomass use is historically very important in China – as it is in many other developing countries – the implications of the scenarios for biomass resources and for land use are considerable. The use of biofuels is already being widely criticised because of its negative impacts on the availability of land for food production, on food prices, and the questionable nature of emissions reductions from some biofuel feedstocks (RFA 2008). Therefore, upgrading to more sustainable and advanced forms of biomass use is assumed in all four Tyndall Centre scenarios.

In power generation, the Tyndall Centre scenarios include relatively large contributions from power plants fuelled by biomass. This contribution ranges from 62 to 152GW of capacity. The biomass used in these plants includes waste products and biogas as well as new biomass crops grown specifically for energy production. Nevertheless, these capacities are much larger than any investments made to date in biomass power generation, and the implications for land use and wider sustainability would need to be assessed carefully.

The Tyndall Centre scenarios include significant use of biofuels for transport by 2050. The annual consumption in 2050 ranges from 158 Mtoe in scenario 4 to 285 Mtoe in scenario 2. By comparison, production so far is very small. In 2007, China produced 1840 million litres of ethanol (1 Mtoe) and 114 million litres of biodiesel (0.08 Mtoe). Converting these and the scenario figures to litres and deriving their implications for land use is difficult because this depends on a range of factors. Biofuels differ significantly in their energy content and the productivity of land use (FAO 2008). Within the scope of this report, it is only possible to produce illustrative figures. For example, if our scenarios were met only from ethanol produced by a first generation process (e.g. from sugarcane), this would correspond to a range of 290-520 billion litres of biofuel. Assuming current rates of productivity, land use would be 64-115 million hectares. This is similar to the range of land areas required for all countries to meet their 2020 biofuel targets (RFA 2008). It also represents a large proportion of China's total cultivated land, which is 130 million hectares in 2005 according to the official statistical yearbook (NBS 2006).

In the light of this illustration, it is clear that the contributions of biofuels included within the Tyndall Centre scenarios could only be sustained if there is significant use of second or even third generation biofuel technologies. These technologies could significantly reduce the requirement to use cultivated land (many could be grown on marginal or uncultivated land), use non-food crops and wastes, and could potentially yield more energy per hectare of land use (IEA 2008c). However, such technologies are not without potential drawbacks and could lead to significant effects on soil fertility for example (FAO 2008). Looking further ahead, third generation technologies such as the use of algae can potentially be produced in sea water – and would therefore only require minimal land use. However, for there is a long way to go before second and third generation technologies will be commercially available.

Hydro power is another renewable energy source that is already extensively used within China. China has 145GW of hydro capacity installed (State Council 2008). There is a government target for this to increase to 300GW by 2020. All four of the Tyndall Centre scenarios foresee a similar level of hydro power expansion – to around 400GW by 2050. The contribution of hydro power has deliberately been limited to this level because this is the potential resource that is commonly cited. Given the controversy surrounding the Three Gorges project, it is likely that exploiting all of this resource successfully will not be a straightforward process. Negative impacts on river systems, on local populations, and on water resources could outweigh the emissions reductions that this full exploitation would achieve.

A final important issue is relevant to this discussion of energy resources – both fossil and non-fossil. Several of the new energy technologies which are prominent within the Tyndall Centre scenarios use raw materials which could be subject to resource constraints and/or price volatility – particularly if their use expands on a global scale (Angerer, Marscheider-Weidmann et al. 2009). These impacts could affect commodity metals such as copper and tin, and more specialist elements such as gallium (used in thin film solar PV cells) and platinum (used in fuel cells as catalysts). This, in turn, could negatively affect the economics of some low carbon technologies and partially outweigh any benefits of scaling up and mass production. However, the same caveat applies to these raw materials as to fossil fuel and uranium resources. Advances in technology could expand the available global reserves, reduce prices or lead to substitution of these materials for others with better availability.

Energy security

Energy security has risen up the global political agenda during the past few years. For Chinese policy makers there are many reasons for this including an increasing reliance on oil imports, rapid increases in oil and gas prices (particularly in 2008), and power blackouts due to insufficient investment in new power transmission capacity. As in other countries, the key threats to energy security have the potential to affect prices and availability of energy sources. For a developing country like China, price security is particularly important because many Chinese citizens still live on very low incomes. Regulations to maintain low prices for these citizens will be costly to the government if commodity prices are high.

Energy security is commonly discussed as a geopolitical issue, particularly in countries like China that are import dependent with respect to some fossil fuels (Yergin 2006). However, there are also many other dimensions to energy security. As recent Chinese experience demonstrates, threats to the security of energy supplies can be domestic as well as international (Watson and Scott 2008). Therefore an assessment of the energy security implications of the Tyndall Centre scenarios needs to take the full range of potential threats. Furthermore, such an assessment needs to consider the overall resilience of the energy system to this range of threats (Stirling 2009).

This brief assessment focuses on four main categories of threat to energy security which were initially developed to analyse strategies for the UK (Watson and Scott 2008). The categories are fossil fuel scarcity and external disruptions, lack of investment in infrastructure, technology or infrastructure failure, and domestic activism and terrorism. These generic categories are equally applicable to China, though the salience of particular energy security threats will obviously differ between the two countries.

Fossil fuel scarcity and external disruptions

Fossil fuel dependency – particularly the dependency on oil imports – is already an important driver of policy. In China's energy White Paper of 2007, there are many references to the inadequacy of its domestic energy resources (State Council 2007). When China first became a substantial oil importer several years ago, a debate ensued about the consequences for geopolitical security. Whilst some analysts were concerned that China would compete with established oil importers, others foresaw a more co-operative future in which China became more integrated into international energy markets (Downs 2004). Although the reality of Chinese policy falls between these two extremes, China's demand for energy has already had a major impact on the world oil market – for example by contributing to the high prices seen in 2008. In addition to stepping up efforts to secure international supplies through China's national oil companies and pursuing policies such as a strategic petroleum reserve, the Chinese government has become progressively more ambitious in its push for greater energy efficiency (Andrews-Speed 2009).

The implications of the Tyndall Centre scenarios for fossil fuel demand in China have already been explored in this section. If current estimates of fossil fuel reserves are correct, the scenarios imply a substantial contribution to global resource depletion. China's dependence on imports of oil is very likely to continue – and to increase. Gas use within the scenarios is also likely to come from both domestic and foreign sources. In principle, coal demand within the scenarios could be met from Chinese sources. But it is probable that significant imports will be used for economic and technical reasons. Across these three main fossil fuels, there will therefore be continuing risks to availability and prices – whether these are due to the physical depletion of resources or 'above ground' factors such as under investment or conflict.

The practical implication of these trends is that geopolitical energy security risks are likely to remain relevant in China for the foreseeable future. Even if China is successful in developing within the carbon budgets that guide the scenarios, fossil fuel use will remain substantial. This message is particularly important since the scenarios incorporate large improvements in energy efficiency. The most ambitious scenario for energy efficiency (S1) includes a reduction in China's energy intensity by 50% between 2005 and 2020, with a further reduction to 13% of current levels by 2050. This goes well beyond the decoupling between energy demand and economic growth that has characterised most of the last 30 years of China's development.

Given that energy efficiency alone is unlikely to be a sufficient strategy to mitigate risks to energy resource availability, many of the other strategies that are currently being pursued will remain important. These include policies such as seeking a diversity of sources of fossil fuels (both domestic and international), providing incentives for a diversity of supply routes, and the development of strategic storage capacity.

Lack of investment in infrastructure

Whilst energy security is often discussed as a geopolitical issue, investments in energy infrastructures within countries can have an important impact. A lack of timely investment in oil refinery capacity, electricity generation and transmission assets or gas storage facilities can all lead to supply disruptions or energy price increases.

China's rapid growth over the past few decades has been accompanied by periodic shortages of energy. In the mid-2000s, there were frequent blackouts in some areas of China as investment in power generation capacity failed to keep up with demand (Xinhua News Agency 2004). There have also been shortages of coal for some power stations due to bad weather, and problems caused by electricity transmission capacity bottlenecks.

The Tyndall Centre scenarios have extensive implications for investments in new energy infrastructures. As noted elsewhere in the report, the rates of deployment required to realise the scenarios are unprecedented in some cases. Whilst this report has not identified the potential costs of this investment in any detail, the availability of strong enough economic incentives and sufficient resources are essential if such deployment rates are to be sustained. This applies to supply side investments in electricity generation capacity (both large and small scale), fuel processing and transmission industries, infrastructure to process biofuels or provide electricity for transport, and CO_2 pipelines for carbon capture and storage. It also applies to energy end-use infrastructure that has a particular role to play in minimising the required growth of energy supply infrastructure. For example, this would include the rapid introduction of more efficient vehicles and substantial rates of construction of new buildings and retrofitting.

In power generation at least, China's recent history suggests that such rates are in fact possible. Over the past few years, power plant capacity in China has increased by almost 100GW a year. None of the scenarios include capacity additions at a significantly higher rate than this – in many cases the rates of increase are lower. However, the key difference is that the scenarios include substantial contributions from technologies other than coal and hydro to energy system development.

This difference between recent and future deployment trends raises a further important issue for the electricity system. The Tyndall Centre scenarios include substantial new generating capacity which has intermittent output such as wind and solar. Some scenarios also include large contributions from other inflexible plant such as nuclear power. As previous Tyndall Centre research has illustrated, scenarios that describe a low carbon electricity system can have serious deficiencies when it comes to matching supply and demand every hour of the day, 365 days per year (Watson, Strbac et al. 2004). There are several ways around this. The traditional view is that more flexible fossil fuel capacity will be required to balance intermittency. This additional capacity could mean more emissions and might be difficult to fit within the overall carbon budget. But developments in technology – especially in the more innovative first two scenarios – could mean that more creative solutions are available. This could include smart grids, active demand side management and storage capacity in electric vehicles or for hydrogen.

Technology or infrastructure failure

Technology or infrastructure failures can occur for a variety of reasons, and can have serious impacts on energy security. Such failures can arise for mainly technical reasons, or could be due to external stresses such as extreme weather. An example of the former is the series of failures that affected advanced gas-fired power plants in several OECD countries the 1990s. Within the latter category, extreme weather events such as Hurricane Katrina have affected offshore oil installations in the Gulf of Mexico. Whether or not China develops within the carbon budgets as set out in the Tyndall Centre scenarios, climate science predicts that such extreme weather events will become more frequent – and that China will have to adapt to its changing climate.

Failures are normal features of all large infrastructure systems. In many cases, they are not serious and do not substantially affect operation due to built in redundancy – or spare capacity in the system. In the case of energy, this reinforces the need to pursue security strategies that strengthen the resilience of energy systems to such failures. Diversity is often put forward as a key principle for such strategies. At present, China's energy system is not particularly diverse with respect to energy sources due to the dominance of coal. But diversity can also be applied to the sources of this coal, and the routes it takes from mines to centres of demand.

The Tyndall Centre scenarios include a substantial improvement in China's energy and electricity system diversity. This improvement is potentially greater if a particularly diverse mix of renewables were deployed. For example, China's primary energy mix in 2005 comprised coal (65%), oil (16%) and renewables (16%). The scenario with the highest energy demand growth (S4) reaches a more diverse position by 2050 – including coal (31%), renewables (27%), oil (19%), gas (13%), biofuels (5%) and nuclear (5%). There is one caveat to this positive assessment. Diversity does not only mean having many options, supply routes or interconnections in an energy mix. It also depends on the balance between these options and how different they are from each other (Stirling 2007). Some vulnerabilities may affect more than one option or supply route if they are sufficiently similar to each other. Therefore a full analysis of diversity within future energy systems needs to take such factors into account.

Another strategy for increased resilience to deliberate disruptions and technical failures that is sometimes put forward is energy system decentralisation (Coaffee 2008). Some of the Tyndall Centre scenarios (S1 for example) include a greater emphasis on such local energy production than others. Whilst the deployment of more decentralised energy infrastructure can increase redundancy and minimise the impact of disruptions, the energy systems in such scenarios would require greater levels of innovation in new network management technologies and/or greater scope for demand side flexibility to balance supply and demand.

Domestic activism and terrorism

There are frequent reports of civil unrest within China, for example in response to some factory closures. The Chinese government is also concerned about the potential for terrorist attacks – both within the Chinese mainland and in the wider East Asian region. A particular concern for the government is that 70-80% of China's oil imports pass through the Malacca Straits between Indonesia and Malaysia. This makes such imports vulnerable to terrorist attack and piracy as well as international conflict (Lees 2007).

It is difficult to make any precise judgements about the threat posed by such incidents to energy security. Evidence that such threats have had an impact in the past is scarce. Given the continuing reliance on fossil fuels within the Tyndall Centre scenarios, the potential for terrorist disruption of energy supplies would remain if these scenarios were followed. Vulnerability to civil disruption would partly depend on the nature of infrastructure development within these scenarios. Decentralisation of energy supply infrastructure within China – so that there is resilience within the power system, the distribution of coal and the distribution of road transport fuel – would make China's energy systems less vulnerable to such disruption. Diversification of international supply routes, as the Chinese government is seeking to do to reduce the amount of oil imported via the Malacca Straits, could also reduce this vulnerability.

7. Towards low carbon growth

This report has shown how China could develop within a range of cumulative carbon emissions budgets. If any of these development pathways were realised in practice, and other countries took commensurate action in the period to 2050, there is a significant chance that the most serious impacts of climate change would be avoided. As noted earlier in the report, these pathways are not intended to be prescriptive. They are designed to illustrate just some of the possible ways in which China could reconcile the twin imperatives of development and climate change mitigation.

As discussed in section 6, the pathways described in our four scenarios have wide ranging implications for resource use and energy security. They also describe far reaching changes in China's industrial structure and its energy infrastructure. The policy implications of the scenarios are extensive. This final section of the report will discuss both the overall implications for China's policy approach to climate change and energy – and some more specific implications for policies to support low carbon energy system development.

China's climate change and energy strategies

There is much discussion at present about the concept of low carbon growth, particularly in the context of developing countries. Developing countries such as China have repeatedly called for climate change mitigation to be addressed within an overall framework of sustainable development (State Council 2008). The Tyndall Centre scenarios provide one set of illustrations of low carbon development for China. They demonstrate how economic growth can be sustained at an average rate of 5-6% per year over the period to 2050 whilst carbon emissions are constrained within cumulative budgets of 70-111GtC. There is an important caveat to this. The scenarios described in this report have not been produced using a macro-economic model. Whilst many such models are limited in their ability to plausibly analyse radical changes in energy systems and economies over many decades, complementary economic analysis of this kind could help to test our assumptions and analysis.

These rates of growth are lower than the average Chinese growth rates of the past two decades. However, they remain high by international standards. It has been argued that China's vast population in rural area means that its growth needs to continue at 10% per year in order to create enough jobs and to continue to lift its citizens out of poverty. There are therefore questions about the extent to which this lower rate of growth can also square climate change mitigation with social stability and poverty alleviation. However, it is plausible to assume that 10% growth rates will not last forever. In all of our scenarios, China's economic structure has changed radically by 2050: and is similar to the current structure of leading OECD economies such as the USA and Germany. Such economies have much lower growth rates as their economies are mature.

The scenarios in this report clearly illustrate the benefits of early action to slow emissions growth, and to eventually move China onto a downward emissions trajectory. Slowing growth in emissions as soon as possible, followed by reductions from 2020 (as in S1) appears to yield a more feasible future than a trajectory in which emissions continue to grow rapidly and only begin to fall in 2030 (as in S4). The rates of decline required in the latter case are much higher and are therefore likely to be much more difficult to achieve. The lower carbon budget of 70 GtC used in this report is impractical if emissions continue to grow at the relatively rapid rate until 2020. These insights follow clearly from the cumulative emissions approach that has been used. This is more informative than an analysis that only discusses percentage emissions reduction targets which are often long term and well beyond current policy time horizons. Of course, another way in which China's future emissions trajectory could be made more plausible is to allocate a large cumulative budget to China. Both scenarios S2 and S4 in particular benefit from this since the larger budget buys time for a later transition to a lower carbon development pathway.

All four scenarios discussed in this report are extremely challenging and ambitious. They describe extensive changes in technologies across the Chinese economy – from power generation to buildings and transport systems. They also include changes in lifestyles and behaviours, and imply extensive changes in policies, institutions and regulations. In addition, they show that low carbon growth can mean more than the deployment of a new set of technologies to meet carbon mitigation goals. The Tyndall Centre scenarios have consciously drawn on the contemporary Chinese policy debate about the energy intensive model of growth that has been followed recently – and the need for economic restructuring and innovation in higher value added industries to help correct imbalances in this model. To a greater or lesser extent, the scenarios show how such a shift could be part of China's low carbon development story.

As many commentators have argued recently, other benefits of this type of development could include the creation of new firms, industries and jobs (Bowen, Fankhauser et al. 2009). Low carbon growth could be one way for countries such as China to overcome the current economic crisis. Indeed, the Chinese government's economic stimulus package of RMB 4 trillion yuan (£400bn) includes significant funding for environmental projects. Well before 2050, China could become a global leader in critical low carbon technologies as well as a country in which they are widely deployed.

Within the scenarios, there is considerable variation in the speed and direction of innovation. For example, scenarios S1 and S2 include more radical and rapid technical change which yields a quicker slowdown in emissions growth. S4 follows a more incremental pathway – though emissions have to fall very rapidly once a turning point is reached in 2030. This is achieved by a range of measures including a particularly large scale deployment of carbon capture and storage. The more radical scenarios tend to emphasise more pervasive energy system innovation. Although such radical changes in technical systems have occurred many times in the past (Freeman and Louca 2001), history shows that deliberate government action is rarely the main reason for such changes.

Whilst some of the technologies and measures that are included in the scenarios are already well established, many others are still in development. Therefore, there is a key role for public and private actors to develop and deploy these technologies. Incentives will be required to support this process of research, development an demonstration and deployment (R,D,D&D) – with tailored programmes to reflect differences in technology status, types of investors and market realities. New institutions to foster low carbon innovation, experimentation and deployment will also be important. Proposals that focus on developing countries such as low carbon innovation centres, put forward by Carbon Trust (Carbon Trust 2008), and Chatham House's idea of low carbon zones

(Chatham House 2007) are both good examples of such incentives and institutions.

Innovation is also a process with a strong international dimension due to the significant role of international firms and markets. In the area of climate change, there is a particularly important debate about the extent to which developed counties should assist developing countries with low carbon technologies as part of a post-2012 deal (Ockwell, Watson et al. 2007). Developing countries such as China rightly argue that promises in this area have been made repeatedly at international environmental summits since the early 1970s (Economy 2005). However, there has been little action to make good on such promises – perhaps with the exception of investment through the Clean Development Mechanism and the new World Bank Climate Investment Funds. For this reason, it is essential that the new post-2012 framework includes further substantive measures to improve international collaboration between firms in developed and developing countries. Although China is a middle income developing country with significant capacity in some low carbon technologies, substantial financial and other assistance is required to help Chinese firms upgrade their capabilities. This is particularly the case in the more traditional heavy industries in which Chinese firms lag well behind the global leaders.

Critical issues for low carbon development in China

The Tyndall Centre scenarios include a wide range of low carbon technologies and other measures in order to remain within the constraints of cumulative emissions budgets. It is not the intention to provide a detailed discussion of all of these here. However, it is possible to point to some of the most critical technologies and measures that are incorporated in the scenarios – and the extent to which these require policy action in the short to medium term to maximise the chance that they could be implemented when required.

As with many analyses of climate change mitigation, a key area in which more action is required in China is energy efficiency. As stated earlier in this report, China already has ambitious targets for improving the efficiency of its economy. Specific energy efficiency measures have also been proposed or implemented in buildings, industry and transport. However, the history of success in this area is mixed – with some notable successes and some periods in which progress on efficiency has been reversed (Andrews-Speed 2009). The Tyndall Centre scenarios build on and extend the ambitions in current policy targets. This is necessary to at least partly offset demand growth due to increased mobility, higher incomes and higher consumption as China continues to develop. In the absence of such sustained action to improve efficiency, the scenarios would be even more ambitious in the need for low carbon energy infrastructure and social change. It will therefore be essential for energy efficiency measures to be sustained and intensified further across the economy.

The power generation sector in China continues to grow rapidly in all scenarios. Within this, there are some extensive developments of renewable electricity generation and of carbon capture and storage. Renewable energy technologies are therefore a key area for government policy action. Such action should support a range of renewable options including those that are currently most important (wind and hydro) and potential new options (e.g. wave and tidal). Our scenarios suggest that the current strategy which focuses on the deployment of renewables and policies to support the growth of renewable energy industries should be continued and strengthened if ambitious renewables development is desired.

With respect to CCS, Chinese power companies have understandably been cautious. Integrated CCS systems have not been deployed anywhere in the world at full scale. CCS systems will impose significant energy penalties at plants where they are installed. For a developing country like China, such penalties mean that valuable power is not available to help meet demand which is growing rapidly. However, this does not mean that Chinese power companies should wait to demonstrate CCS on coal fired power plants. The EU-China NZEC (near zero emissions from coal) feasibility study is a start. Building on this, there are strong reasons to make international financial assistance available for a full scale demonstration of CCS in China at the same time as the demonstrations planned in many OECD countries over the next few years. Without CCS as an option, it will prove much more difficult for China to develop within a carbon budget. In contrast to CCS, nuclear power has a less prominent role – but is significant in one of our scenarios.

The Tyndall Centre scenarios also include significant power and heat generation at smaller scales. Off grid power generation and more decentralised energy systems (e.g. solar hot water panels and CHP systems) are particularly important in some of the more innovative scenarios. This leads on to the importance of new smarter grid technologies, and information, communication and control technologies to better integrate supply and demand.

Transport has been a particularly rapid source of energy demand growth in China in recent years. It is also an area in which there has been active policy action to mitigate some of the environmental side effects of this growth (Gallagher 2006). Although a continuation of this trend means that China's oil consumption will rise rapidly in the scenarios, the scenarios include fundamental changes over the coming decades. This includes significant efficiency improvements, modal shifts and switches to biofuels and electric vehicles. There will be a need to develop and evaluate new transport technology options for both public and private transport applications. As noted in the previous section, the widespread use of biofuels in China could only be realised if second or third generation technologies were successfully developed and commercialised. Resource constraints mean that the use of first generation biofuels on a larges scale is likely to be impractical. With respect to electric vehicles and the related possibility of hydrogen vehicles, Chinese firms have started to make some early headway. This report has already noted the case of the BYD plug-in hybrid electric vehicle, one of the first such vehicles to be available commercially in the world. Together with development in other sectors such as low carbon electricity or hydrogen generation and

8. References

new infrastructures on roadside for quick recharging, there is a huge potential for electric vehicles in future road transport.

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