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Technology and carbon mitigation in developing countries: Are cleaner coal technologies a viable option?

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Background Paper for Human Development Report 2007

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Introduction

This background paper for the 2007 Human Development Report is part of the cluster: *Living within a carbon budget – the agenda for mitigation*. It focuses on the development and adoption of cleaner coal technologies that can reduce the environmental impact of coal use. Of particular importance in the context of climate change are those technologies that can potentially reduce emissions of CO_2 from the combustion of coal. The paper draws on international experience of these technologies and focuses in particular on three industrialising countries that are heavily dependent on coal - China, India and South Africa. Coal is likely to continue to be important for these countries for decades to come. If the growth of their economies is to be compatible with climate stabilization, there is a clear need for cleaner coal technologies.

The transfer of low carbon technologies – including some cleaner coal technologies - could play a pivotal role in creating incentives for developing countries such as China and India to enter a post-2012 Kyoto agreement. However, current multilateral provisions for international technology transfer are relatively weak, with a focus on project-based approaches under the Clean Development Mechanism. At the same time, the development, diffusion and financing of new technologies in energy-intensive sectors is more complex than is sometimes assumed by proponents of technology transfer. This paper explores these complexities and provides some possible ways forward to help accelerate cleaner coal technology transfer and deployment.

The paper comprises six main sections. Section 1 of the paper starts with an overview of low carbon technology transfer including key issues and barriers. Section 2 provides an overview of technology transfer activities and mechanisms within the UN Framework Convention on Climate Change. Section 3 discusses the rationale for investing in cleaner coal technologies as an important part of global efforts to mitigate carbon emissions. It also provides a definition of cleaner coal technologies, and shows the extent to which the various technologies under this heading can reduce carbon emissions. This is then followed by section 4 which provides a more detailed overview of these technologies and assesses their current status. Section 5 discusses the experience of cleaner coal technology deployment in three industrialising countries: China, India and South Africa. Within each country case study, future projections of coal use in the electricity sector are used to illustrate the potential impact of cleaner coal technology deployment on carbon emissions. Finally, section 6 of the paper draws some lessons from the case study and provides some considerations for the design of policies to accelerate the deployment of these technologies.

1. Low Carbon Technology Transfer to Developing Countries

This section will give a brief overview of the debate on technology development and transfer as part of a climate change mitigation strategy. This will explain the different types of technology transfer including vertical transfer (often rather simplistically characterized as transfer of technology from the laboratory or test bed into commercial use) and horizontal transfer (transfer from one geographical and/or firm context to another). It will also note that horizontal technology transfer – which is what most of the debate with respect to climate change focuses on – often needs to be combined with vertical transfer to be effective. In doing so, the section will note that there are different technology transfer flows that can be occur. These range from the transfer of capital equipment to the transfer of underlying technological knowledge that would allow developing countries to develop independent capabilities in low carbon technologies.

The term 'technology transfer' can mean many different things. It has been defined and measured in many different ways and assessed against a wide range of criteria (Schnepp, von Glinow et al., 1990). Technology transfer has therefore attracted attention from a broad range of perspectives including business, law, finance, microeconomics, international trade, international political economy, environment, geography, anthropology, education, communication, and labour studies (IPCC, 2000). This has produced an equally wide range of frameworks and models of technology transfer, but to date no overarching theories have emerged. In his review of research and theory on technology transfer, Bozeman (2000), states that:

> "In the study of technology transfer, the neophyte and the veteran researcher are easily distinguished. The neophyte is the one who is not confused. Anyone studying technology transfer understands just how complicated it can be."

Nevertheless, there are several key definitions, distinctions and insights that have emerged from the broader literature on technology transfer that are relevant when considering the transfer of low carbon technologies between developed and developing countries.

Schnepp et al. (1990: 3) define technology transfer as "… a process by which expertise or knowledge related to some aspect of technology is passed from one user to another for the purpose of economic gain." Technology transfer is a term that relates to any type of technology, not just low carbon technology. Within the current climate of environmental concern, however, the economic gain that Schnepp et al. speak about in their definition of technological transfer can be interpreted in a wider context that includes the economic benefits provided by the environment as a source of natural resources that feed into the economic process and a sink for emissions that result from the economic process. In the case of the transfer of low carbon technology, these economic benefits are associated with the mitigation of the future costs associated with climate change (See Ockwell and Lovett, 2005). As with any technology transfer, however, low carbon technologies may also yield financial benefits to the companies involved in the transfer process.

Types of technology transfer

One important distinction in the literature on technology transfer is between vertical technology transfer (the transfer of technologies from the research and development (R&D) stage through to commercialisation) and horizontal technology transfer (the transfer from one geographical location to another). Schnepp et al.'s (1990: 3) definition quoted above refers to horizontal technology transfer. In reality, this distinction between horizontal and vertical technological transfer is unlikely to be so distinct. In the case of low carbon technology transfer between developed and developing countries, which this study is primarily interested in, there is likely to be elements of both. The transfer of technology from one country to the next represents horizontal transfer. But this transfer may also involve a degree of vertical transfer as many low carbon technologies are currently pre-commercial or supported technologies and undergo development towards commercialisation within the new country context.

Technology transfer may also take the form of internalised or externalised transfers by trans-national companies (Ivarsson and Alvstam, 2005). Internalised transfers usually form part of a package of foreign direct investment (FDI) where access is provided to a range of technological, organisational and knowledge assets as well as marketing experience and brand names. Externalised transfers are those made to firms outside of the direct ownership or control of the company transferring the technology. This occurs through initiatives such as minority joint ventures, franchising, distribution agreements, sales of capital goods, licenses, sub-contracting, or original-equipment-manufacturing arrangements. R&D can also generate beneficial external linkages within recipient countries but is dependent on the availability of adequate R&D facilities.

The centrality of knowledge transfer

A key insight to emerge from the literature is that technology transfer is not just a process of capital equipment supply from one firm to another. Comprehensive technology transfer also includes the transfer of skills and know-how for operating and maintaining technology hardware, and knowledge for understanding this technology so that further independent innovation is possible by recipient firms (Bell, 1990). This process can be broken down into two stages. The first stage is the supply of technology to recipient countries. This can be split into three separate technology flows, namely:

A. Capital goods and equipment
B. Skills and know-how for operating and maintaining equipment
C. Knowledge and expertise for generating and managing technological change

The second stage involves building on these three technology flows to develop new capacity within the recipient country. This capacity consists of both new production capacity and new technological capacity. It is this new capacity for production and technological innovation that is most likely to ensure successful technology transfer and long term advances in technology development in recipient countries (Worrell, van Berkel et al., 2001).

Within the economics literature there is a divide between two different schools of thought concerning how technology transfer translates into new technological capacity within recipient countries. Both schools of thought accept the long term importance of knowledge for developing new capacity within technology importing countries. They are, however, divided as to how this knowledge is generated. Traditionally, commentators tended to base their ideas around neo-classical 'accumulation theories' of technology transfer (Nelson and Pack, 1999; Ivarsson and Alvstam, 2005). This approach assumed that the learning that underpins capacity building within developing countries automatically followed capital investments. In this view, capacity building in developing countries would be encouraged by increased capital investment facilitated, for example, by a more competitive economic policy environment.

More recently, however, 'assimilation theories' of technology transfer have tended to gain greater support from the analysis of empirical evidence on technology transfer (Nelson and Pack, 1999; Worrell, van Berkel et al., 2001; Ivarsson and Alvstam, 2005). Assimilation theories take a more evolutionary view of the technology transfer process and stress that learning is a key factor in making capital investments successful. Knowledge transfer therefore becomes central to ensuring that technology supply leads to successful capacity building in recipient countries. The availability of knowledge as part of the technology transfer process is not, however, enough on its own. Assimilation theorists also stress the importance of risk taking and entrepreneurship on behalf of firms in recipient countries to facilitate learning. The generation of inter-firm linkages through regular local production by foreign operators is also seen as integral to knowledge generation with external linkages resulting in technological upgrading among local suppliers. In this sense, external technology transfers are more likely to generate new technological capacity in recipient countries than internal transfers which might simply exploit low labour costs (Ivarsson and Alvstam, 2005). Competing in international export markets may also be an issue here in driving awareness of international standards and contracting with developed country firms who demand and facilitate high standards (Nelson and Pack, 1999).

As well as highlighting the importance of using local suppliers, the assimilation view of technology transfer implies that all three flows of technology (flows A, B and C) are important for enabling recipient countries to develop their own technological capabilities. This has been problematic in the past as the predominant type of technology supply to developing countries has tended to focus on the first of these: capital goods and equipment (Bell, 1997; Watson, Oldham et al., 2000). For example, a database of international aid to China's energy sector compiled by Evans (1999a) showed that 80% was focussed on funding construction of new thermal and hydro-power plants. The primary aim of this aid was to finance the export of equipment supplied by foreign firms (Watson, Oldham et al., 2000). Saad and Zawdie (2005) also point out how the transfer of plant and equipment to developing countries have often been based on 'turnkey' and 'product-in-hand' contracts that focused on boosting industrial growth rather than fostering innovation. They also highlight the fact that restrictive terms of contracts between trans-national companies and firms based in developing countries have limited the scope for fostering innovation through 'reverse engineering'. A good example of this is licensing within the global power plant equipment industry (Watson, 1997). The leading companies in this industry have provided licenses to developing country firms for the manufacture of equipment such as gas turbines. However, these licenses exclude the manufacture of the most 'high tech' components such as the first row of turbine blades which incorporate advanced materials, cooling technologies and manufacturing techniques.

Moreover, technology transfer has often conformed to a linear model of relationships between technology suppliers and importers, which precludes knowledge sharing. From the perspective of encouraging the long-term adoption of low carbon technologies in developing countries, it is therefore important that technology transfer includes flows of skills and knowledge as well as capital goods and equipment. Successful examples of purely knowledge-based technology do exist. For example, a joint initiative between China and the Netherlands which established an intelligent transport systems training centre in China is reported to have made a promising initial impact on tackling congestion in Shanghai (van Zuylen and Chen, 2003).

As highlighted by the IPCC's (2000, section 1.4) report on technology transfer, this increasing awareness of the centrality of developing knowledge-based capacity within developing countries has led many people to feel uncomfortable with the term "technology transfer". They argue that it encourages a view of technology as an object and transfer as a one off transaction that maintains dependency on host country suppliers. Suggested alternative terms include 'technology cooperation' (Heaton, Banks et al., 1994; Martinot, Sinton et al., 1997), 'technology diffusion' (Grubler and Nakicenovic, 1991) and 'technology communication' (Robinson, 1991). These tend to emphasise technology transfer as a more dispersed, uncoordinated process that occurs over time with a central emphasis on a two-way relationship between technology suppliers and importers (IPCC, 2000, Section 1.4).

Knowledge transfer and intellectual property rights (IPRs)

Whilst some commentators may, in the past, have been slow to recognise the importance of knowledge transfer, this section has already emphasised that technology suppliers and users see this as centrally important. Supplier firms often take a proactive approach to preserving their commercial interests during technology transfer activities by closely guarding the underlying knowledge relating to their technologies. To do this, they use patenting, selective licensing and other forms of intellectual property rights (IPRs) protection.

The issue from the perspective of supplier companies is that they have often invested large sums of money in developing low carbon technologies and they wish to preserve their competitive position. Furthermore, they are not confident that the legal regime with regard to IPRs is well enough defined or enforced in some developing countries. This raises the question as to whether more tightly defined and enforced IPR regimes might be beneficial to encouraging technology transfer - if the firms that own relevant technologies were able to be confident that the money they invest in R&D was not at risk through imitation in the countries they supply the technology to, they might be more inclined to engage in technology transfer activities.

On the other hand, however, it is questionable whether technology transfer under such tightly controlled IPR regimes would have any long term benefits for the recipient country. It potentially makes it less likely that recipient firms will gain access to the underlying knowledge that is necessary to develop technological capacity within the recipient country. As highlighted above, the development of such technological capacity is central to a country's long term ability to absorb and innovate on the basis of new low carbon technologies. This long term view is also integral to achieving sustained economic development.

The debate over IPR protection in the context of technology transfer has become an increasingly important issue in international negotiations on a variety of issues including public health, biotechnology, trade and food security (ICTSD and UNCTAD, 2003). IPRs have been observed to have both positive and negative impacts on technology transfer (Ockwell and Lovett, 2005). A joint study by UNCTAD and the International Centre for Trade and Sustainable Development (2003, p.85) notes that:

> "It is fair to say that stronger IPRs reduce the scope for informal technology transfer via imitation, which was an important form of learning and technical change in such economies as Japan and the Republic of Korea (not to mention the United States). TRIPS [Trade-Related Intellectual Property Rights] has narrowed the options in this regard and raised the costs of imitation. At the same time, stronger patents, trademarks and trade secrets should reduce the costs of achieving formal technology transfer and expand such flows. However, evidence on this is not conclusive."

The study concludes that there is a lot of uncertainty about the impact of intellectual property protection on technology transfer. There is evidence that the effect depends on a number of factors including how developed a country is, what technologies are being transferred and the capacity and structure within the industry concerned (ICTSD and UNCTAD, 2003). Furthermore, the extent of IPR protection has an influence on the kind of technology transfer mechanism that is likely to be favoured by international firms. Strong IPR regimes, tend to encourage technology licensing and joint ventures whereas weaker regimes lend themselves to foreign direct investment (Maskus, 2000).

Some have argued that one way to overcome IPR barriers is for governments to make patents for important technologies publicly available through compulsory licensing or the purchase of licenses with public funds (ICTSD and UNCTAD, 2003). A recent Ministerial Indaba on climate action notes that 'a Multilateral Technology Acquisition Fund could be structured to buy-out intellectual property rights (IPR's) and make privately-owned, climate-friendly technologies available for deployment in developing countries' (van Schalkwyk, 2006) or in a "limited public domain" (Ghosh, 2005)

However, it has also been noted that access to key patents by developing country firms is not a sufficient condition for effective technology transfer. Much of the knowledge relevant to working a patent is tacit. Full use of a patent is likely to require access to a variety of related information sources that are not fully explained in the patent.

Whilst a number of studies have examined IPR related barriers in the field of biotechnology, agriculture and public health (UK Commission on Intellectual Property Rights, 2002; Yamin, 2003), the literature on the specific nature of IPR barriers in the context of climate change is sparse. At present, therefore, insufficient research exists to say with any certainty whether it would be beneficial or counter-productive to make IPRs public property or, alternatively, to tighten up IPR regimes in developing countries. However, recent research by the Sussex Energy Group, IDS and TERI suggests that access to IPRs by recipient companies during the technology transfer process needs to be assessed on a case-by-case basis (Ockwell, Watson et al., 2006). In some cases, access to IPRs might be a necessary part of enabling long term technology transfer, but it is not necessarily sufficient to enable it.

For example, in case of LED lighting in India, industry commentators feel that without improved technological capacity in India in this industry, ownership of relevant IPRs would make little difference to India's ability to manufacture white LEDs (Ockwell, Watson et al., 2006). Another example is IGCC technology (see section 4 of this report), where the key barrier to transfer was not ownership of IPRs but rather a lack of knowledge of whether IGCC will work with low quality Indian coal and the overall lack of worldwide successful commercial demonstration of this technology.

In some cases, in the long term, protection of IPRs for some technologies may not be a barrier to developing technological capacity in recipient countries. One possible example is hybrid vehicles (Ockwell, Watson et al., 2006). Hybrid drive trains are subject to strict IPRs. But, where they have been supplied to other countries, the firms owning the IPRs have had to train engineers and mechanics in the recipient country in fitting and maintaining the drive trains. This implies the potential for companies in recipient countries to develop their own technological capabilities in hybrid drive trains which may also filter through to the wider economy in the longer term. But this could be a slow process raising the issue of time criticality when dealing with technologies that are, by their very nature, desirable to transfer in order to mitigate climate change.

An important issue that needs to be understood in relation to low carbon technologies is whether IPRs as a barrier to technology transfer might vary in importance according to the stage of technology development or the nature of the technology itself. For example, the stage of development of a particular technology may have implications in terms of the level of private investment already made in a technology and the level of returns that IPR owners need to derive before they are happy to release the IPR. Cleaner coal technologies at an early stage of development such as carbon capture and storage (CCS) might have more riding on them in this sense than commercially available cleaner coal technologies such as super-critical boilers.

One possible route forward in addressing IPR issues in the context of technology transfer is international collaboration on low carbon technology development. This could be on the basis of international collaborative R&D initiatives on technologies that are at a very early stage of development. As these technologies would be collaboratively developed, the IPRs could be structured to benefit the various partners involved, including with the aim of making the IPR available as a free or low cost public good. This kind of international collaborative R&D based approach has the added benefit of enabling knowledge sharing between collaborators which could aid long term capacity building in developing countries. The idea of a Global Research Alliance was put forward by the UK Commission on Intellectual Property Rights as a way of linking developmental objectives (capacity strengthening and sustainable development) with the more commercially driven IPR framework (UK Commission on Intellectual Property Rights, 2002).

In cases of technologies covered by existing IPRs, international initiatives and international funds, such as those established under the UN Framework Convention on Climate Change, could potentially play a role in facilitating role in negotiating licences or buying down the costs of specific technologies to make them more widely accessible - as has happened in the case of the Montreal Protocol dealing with ozone depletion. Insights from how global private/public partnerships have addressed issues of access to proprietary technologies in other sectors, such as public health, might also provide a fresh approach to the issue of technology transfer.

The potential for new kinds of global public/private partnerships, drawing on the experiences of global arrangements that have been agreed internationally to support access to anti-retroviral drugs for low income countries, have not been fully explored in the climate context. More detailed work analyzing the potential application of these approaches to low carbon technologies, bearing in mind the unique features of climate change, might create a fresh approach to discussions. Collaborative R&D initiatives are discussed in more detail in the concluding section of this report.

2. Current Arrangements for Technology Transfer in the UNFCCC

Technology transfer usually takes place within the private sector. As such, the mechanisms by which low carbon technology transfer is facilitated in the private sector are no different to the mechanisms that are routinely used for the transfer of other kinds of technology. These include, for example, joint ventures and foreign direct investment (FDI). The public good nature of low carbon technologies, however, implies a clear incentive for government involvement in facilitating, or speeding up the process of technology transfer. There are two main reasons for government involvement in technology transfer at the international level:

1. Reducing carbon emissions contributes to reducing the economic, social and environmental costs of climate change. The external costs of carbon emissions are not yet fully reflected in mechanisms that price carbon such as the European emissions trading scheme and the Clean Development Mechanism; and
2. Many low carbon technologies are currently at pre-commercial or supported commercial stages of development and many therefore require some form of government support to facilitate their wider adoption.

The need for international action to facilitate the transfer of low carbon technologies is explicitly recognised by Article 4.5 of the UN Framework Convention on Climate Change (UNFCCC - "the Convention"):

> The developed country Parties and other developed Parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention. In this process, the developed country Parties shall support the development and enhancement of endogenous capacities and technologies of developing country Parties. Other Parties and organizations in a position to do so may also assist in facilitating the transfer of such technologies.

The Marrakesh Accords

As part of the Marrakesh Accords at COP7[2], a framework was established with the aim of facilitating actions to implement Article 4.5 of the Convention[3]. The framework has five themes:

1. Technology needs & needs assessments

This involves an analysis by recipient countries of their perceived priority low carbon technology needs against which technology transfer initiatives under the Convention can be targeted.

2. Technology information

A web portal under an initiative known as TT:CLEAR[4] has been established to facilitate the flow of information between different stakeholders, including technology recipients and suppliers.

[2] COP refers to a Convention of the Parties to the UNFCCC. These are held annually.
[3] See the annex to decision 4/CP.7 http://unfccc.int/resource/docs/cop7/13a01.pdf#page=22

3. Enabling environments

This part of the framework addresses the need for action at national levels to remove potential barriers to technology transfer. It includes initiatives such as implementing fair trade policies, removal of technical, legal and administrative barriers, creating stable macro-economic conditions and transparent, enforceable regulatory frameworks.

4. Capacity building

Technological capacity building in developing countries is essential to the long term uptake and development of low carbon technologies in developing countries. This part of the framework seeks to encourage the strengthening and development of technical and scientific skills, capabilities and institutions in non-Annex I countries.

5. Mechanisms for technology transfer

The Marrakesh Accords also provided for the establishment of an Expert Group on Technology Transfer (EGTT). The EGTT is nominally responsible for the implementation of Article 4.5 of the Convention within the context of this five part framework. EGTT members are nominated by the parties. Its 20 members are drawn from developing nations, small island nations, Annex I Parties (i.e. developed nations) and relevant international organisations. In particular, the EGTT has been involved in the development and collation of Technology Needs Assessments and the creation and administration of the TT:CLEAR information clearing house. The EGTT's mandate was due to expire in 2006. Due to disagreement among the Parties, particularly between developed and developing countries, as to how to proceed following its expiry, it was agreed at COP12 that the EGTT should be kept alive for one more year pending another discussion at COP13 in 2007.

The Clean Development Mechanism (CDM)

The arrangements outlined above have an important role to play in the long term facilitation of low carbon technology transfer. At present, however, the Clean Development Mechanism (CDM) under the Kyoto Protocol of the UNFCCC is the only concrete mechanism that provides the potential for low carbon technology transfer. The CDM has an ambitious remit. It allows investors from Annex I countries to generate Certified Emissions Reductions (CERs) by investing in projects that reduce greenhouse gases in developing countries. The CDM does not have an explicit technology transfer remit but it is recognised that it might facilitate technology transfer to developing countries where emissions reduction projects involve technologies not currently available in host countries. An analysis of all 860 registered CDM projects to date by Haites *et al*. (2006) demonstrates that around a third of these projects intend to include the transfer of either equipment or hardware or both. An analysis of 63 CDM projects registered by January 1st 2006 by de Coninck (2006) found that almost 50% of projects used technology from outside of the host country. According to Haites *et al*.'s (2006) analysis, projects involving technology transfer account for around two thirds of emissions reductions achieved under the CDM (see the final column of Table 1). The plans for technology transfer vary significantly by project type and host country. In India, for example, only 7.3% of CDM projects plan to involve some element of technology transfer compared to 55.1% in China and much as 83.3% in

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[4] See http://ttclear.unfccc.int/ttclear/jsp/index.jsp

Malaysia (see the penultimate column of Table 1). This suggests that host country approval processes can increase the rate of technology transfer under the CDM – - under the CDM host country governments must approve potential projects on the basis of them conforming to host country laws as well as the national priorities that host countries may state as part of the CDM process. It is therefore possible for a country to influence the extent of technology transfer involved in CDM projects via this approval process (Haites, Duan et al., 2006). These results also suggest that local technology is preferred for some types of emission reduction projects. Given the expanding role of the CDM in the future climate regime, more detailed analysis of host country approval processes for CDM may provide useful insights on how the CDM can deliver more technology transfer.

Table 1. Technology Transfer for CDM Projects in Selected Host Countries

Host Country	Number of Projects	Estimated Emission Reductions ($ktCO_2e/yr$)	Average Project Size ($ktCO_2e/yr$)	Technology Transfer Claims as Percent of Number of Projects	Technology Transfer Claims as Percent of Annual Emission Reductions
Argentina	9	3,579	398	77.8%	99.4%
Brazil	160	20,471	128	33.1%	74.1%
Chile	23	3,720	162	17.4%	44.8%
China	69	52,996	768	55.1%	75.9%
Honduras	19	446	23	57.9%	57.5%
India	329	26,595	81	7.3%	34.4%
South Korea	12	12,556	1,046	50.0%	88.2%
Malaysia	18	2,343	130	83.3%	94.8%
Mexico	54	7,303	135	85.2%	91.4%
Nigeria	2	4,044	2,022	0%	0%
Philippines	22	388	18	63.6%	72.8%
Other Host Countries	137	14,930	109	49.6%	50.9%
Total	854	149,369	175	33.5%	65.5%

Source: (Haites, Duan et al., 2006)

These statistics on the CDM suggest that the CDM does have the potential to help facilitate the transfer of low carbon technologies. It must be emphasised, however, that the CDM is at an early stage of implementation and it is therefore too early to judge the actual level of technology transfer that it will facilitate. The strengths and weaknesses of this aspect of the CDM will need closer study as projects are implemented.

Irrespective of the CDM's impact on technology transfer, it is already widely recognised that this mechanism will not facilitate all of the potential low carbon technology deployment in developing countries. A range of national and international routes for additional finance have been developed which include a mix of public and private initiatives (TERI, 2006). Multilateral institutions such as the World Bank are thought to have a particularly important role to play. The Bank has recently outlined some of the additional multilateral finance mechanisms that could be implemented (World-Bank, 2006). It is working on an energy investment framework under the Gleneagles Dialogue that aims to address cost, risk, institutional and information barriers.

Options that have been put forward include a Clean Energy Financing Vehicle that would blend carbon finance and capital grants for highly efficient technologies. They also include proposals to help upgrade the efficiency of existing capital equipment, to provide venture capital, and to develop candidate projects for financing via other mechanisms. Additional analytical work is needed to understand better the factors and circumstance under which these mechanisms might be implemented most effectively.

The Montreal Protocol on substances that deplete the ozone layer is an example of an international agreement that facilitated the transfer of cleaner technology. Technology transfer related specifically to technology geared towards reducing emissions of CFCs (chlorofluorocarbons) and other ozone depleting substances. Via the establishment of a multilateral fund under the Protocol, 5000 projects were established in 139 developing countries that either dealt directly with technology transfer or capacity building (TERI, 2007). This is cited as having eliminated a substantial proportion of worldwide production of ozone depleting substances.[5]

A final initiative worth mentioning here is the Asia-Pacific Partnership on Clean Development and Climate. This is a partnership between the US, Australia, China, India, Japan and the Republic of Korea that focuses on the development and deployment of clean technology. The Partnership has set up several taskforces covering a range of industrial sectors around which it is planned to focus efforts to develop and deploy clean technologies. One of these focuses on technologies for cleaner fossil energy, including carbon capture and storage. The Partnership is based on non-binding agreements and is at too early a stage to be able to judge its practical success in facilitating technology transfer.[6]

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[5] See http://www.multilateralfund.org/ for precise figures and more on the implementation of the Montreal Protocol

[6] See http://www.asiapacificpartnership.org/

3. The Rationale for Cleaner Coal Technologies

The continuing importance of coal

Modern energy systems in many countries still rely heavily on fossil fuels. Whilst energy policies in many countries imply a significant shift towards low-carbon energy sources, most projections show that fossil fuels will continue to play a key role in the medium term. This is particularly the case in rapidly industrialising countries such as India and China. In these countries as well as industrialised countries such as the United States, Germany and Australia, coal is likely to play a large role in energy supplies for many years to come.

The most recent World Energy Outlook from the International Energy Agency is typical, and shows a large increase in global coal demand in the period to 2030. In the IEA's view, this is the case whether or not governments act to reduce energy demand and carbon emissions. Due to rises in overall global energy demand, the IEA's business as usual 'reference scenario' expects coal's share of global energy to remain constant at around 25%.

As Table 2 shows, the IEA expects that most of the increase in coal demand to 2030 will come from developing countries. In addition, the largest share of the increase (81%) will come from the power sector. In 2004, the world's coal fired power plants produced 6917TWh of electricity – 40% of the total. This is expected by the IEA's 'reference scenario' to reach 14,703TWh by 2030. Over half of the increase would come from power plants built in China.

Table 2. Projected global coal demand to 2030 (million tonnes)

	2004	**2015**	**2030**
OECD	2313	2552	2735
Transition Economies	521	575	491
Developing Countries	2766	4215	5647
Total	**5558**	**7328**	**8858**

Source: (International Energy Agency, 2006b).

It is useful to compare these figures with recent projections by the US government (Energy Information Administration, 2006). These see OECD demand for coal rising from 2318 million tonnes in 2003 to 3127 tonnes in 2030. The same study shows non-OECD demand for coal rising from 2691 tonnes in 2003 to 6473 tonnes in 2030. These figures are significantly higher than those from the IEA. Again, the main driver of world-wide demand is growth in China and India.

When interpreting projections such as these, it is important to recognise some of the factors that influence them. First, the agencies such as the IEA rely on national governments to provide data. There is a tendency to provide figures near the top end of any range due to an understandable worry about underestimating demand. History shows a tendency for official projections to overestimate future demand for energy and natural resources[7]. Second, projections are often particularly influenced by recent history. As later sections of this report will show, coal demand growth has been dominated in the last few years by demand from power generators in China – so it is not surprising that projections see this as a key driver for future growth. Nevertheless, neither of these caveats detract from the central message that coal will continue to be very significant for the foreseeable future, particularly in China and India.

Why cleaner coal technologies?

Whilst coal is an abundant and comparatively cheap energy source at present, its use leads to extensive and sometimes severe environmental impacts. Coal burning causes a range of local, regional and global pollution problems. Emissions of particulates and oxides of nitrogen have been the cause of urban smog – famously in London in the 1950s and more recently in developing countries such as China. Coal mining and use have also been the cause of extensive water pollution. In addition, sulphur dioxide emissions from coal combustion are the primary cause of acid rain which has affected many regions of the world including North America, northern Europe and areas of East Asia (e.g. southern China).

More recently, carbon dioxide (CO_2) emissions from coal combustion have been identified as a major cause of unprecedented human induced changes to the world's climate. This impact of coal combustion is now seen as the most important by many developed countries. According to the IEA's most recent projection, CO_2 emissions from power stations alone could increase by 2% per year in the period to 2030 (International Energy Agency, 2006b). Most of this increase is attributed to increasing coal-fired power generation, especially in China and India.

The focus on CO_2 emissions is supported by increasing evidence from bodies such as the Intergovernmental Panel on Climate Change (IPCC). In its contribution to the its fourth assessment report, Working Group 1 of the IPCC reinforced the overwhelming evidence that greenhouse gas concentrations are rising as a result of human activity – primarily through the burning of fossil fuels (Intergovernmental Panel on Climate Change, 2007). The report notes that carbon dioxide is the most important greenhouse gas. CO_2 concentrations have risen from a pre-industrial level of 280 parts per million (ppm) to 379ppm in 2005. Furthermore, the report concludes that there is 'unequivocal' evidence that this rise in concentrations of greenhouse gases is causing warming of the climate system. A range of scenarios predict that this warming will lead to an average temperature increase of 1.8-4.0°C by the end of the 21st Century. This warming will, in turn, is likely to lead to a range of severe impacts such as increases in severe weather events (heatwaves and cyclones) and sea level rise due to melting of polar ice caps

Whilst the persistence of greenhouse gases in the atmosphere mean that significant further warming is now inevitable, global action to reduce CO_2 emissions would limit the extent of this warming and the severity of the associated impacts. This need for urgent global action is increasingly being recognised by both developed and developing countries. However some developing countries still place more emphasis on tackling the local and regional impacts of coal

[7] For example, UK projections of growth in electricity generation capacity were consistently too high in the 1960s and 1970s, and led to significant over investment. See House of Commons Select Committee on Energy (1981). The Government's Statement on the New Nuclear Power Programme. London, HMSO.

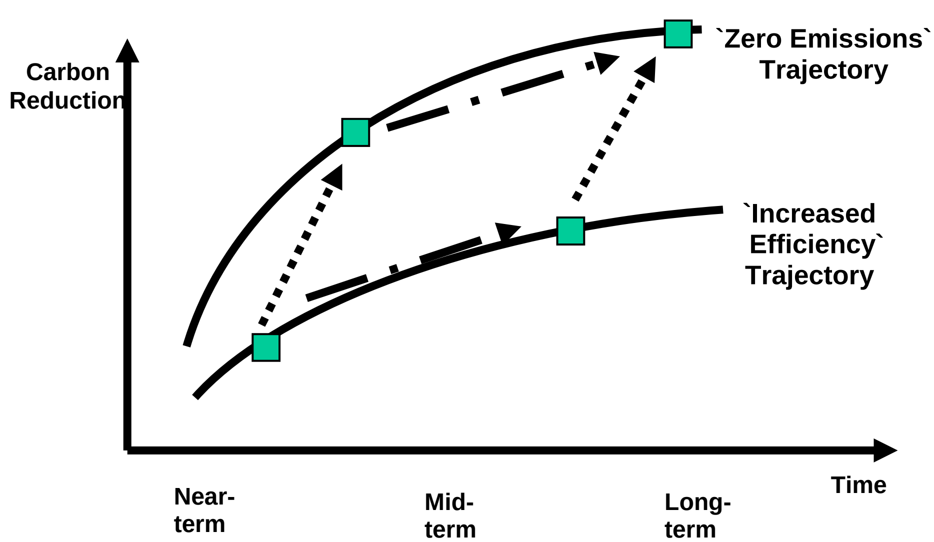
combustion. Problems such as smog and acid rain that have been substantially addressed in developed countries are still pervasive in the developing world.

What are cleaner coal technologies?

The need to mitigate these environmental impacts has driven the development of a variety of technologies designed to burn coal more cleanly and efficiently. Attention has also focused on ‘end of pipe’ technologies to remove undesirable pollutants after combustion. These technologies are collectively known as ‘clean coal’ or – perhaps more accurately – ‘cleaner coal’ technologies. The second ‘cleaner coal’ description recognises that it is not possible to make coal use completely free of environmental impacts. It also conveys the context-specific nature of these technologies. For example, technologies that would have a significant impact in China and India would not do so in OECD countries because their use is already routine. One example is the use of washing/preparation processes to improve the quality of coal before it is burned, something that is sometimes not carried out in some developing countries.

As a general rule, coal-use technologies are regarded as ‘cleaner’ if they offer an environmental improvement over those currently in use. Whilst further details of these technologies and their status are given in Section 4 of this report, it is useful to introduce some examples here to make the definition clear. Low NO_X burners can be installed in power station boilers to reduce emissions of oxides of nitrogen. The addition of flue gas desulphurisation (FGD) equipment can take up to 90% of the sulphur dioxide out of the waste gases from a power plant or other large coal-burning facility. Turning to the main focus of this report, climate change, there are a range of approaches to reducing CO_2 emissions. As Figure 1 illustrates, there are two main routes for this. The increased efficiency trajectory shows that CO_2 emissions can be reduced incrementally – leading to significant reductions over the long term. The zero emissions trajectory envisages the use of carbon capture and storage technology to reduce CO_2 emissions towards zero.

Figure 1. A ‘twin track’ approach to emissions reduction from fossil power generation



Source: (Advanced Power Generation Technology Forum, 2004)

Table 3 provides some figures to support this illustration. It shows the potential impacts of a range of cleaner coal technologies on average CO_2 emissions from coal-fired power plants in China. It shows that emissions can be reduced by 22% by bringing plant efficiency up to the 'international standard' for traditional coal-fired power plants, but they could in future also be reduced by over 90% if carbon capture technology is commercialised and deployed.

Table 3: Carbon emissions from different power plant technologies

	Approx CO_2 emissions (g/kWh)	**Reduction from Chinese average**	**Lifetime CO_2 savings (m tonnes)***
Coal-fired plants:			
Chinese coal-fired fleet average, 2006	1140	-	-
Global standard	892	22%	73.3
Advanced cleaner coal	733	36%	120.5
Supercritical coal with carbon capture	94	92%	310.8
Other energy supply technologies:			
New gas-fired power plant	330	71%	240.6
Nuclear power plant	Small**	>95%	**
Wind power plant	Small**	>95%	**

* Lifetime savings assume a 1GW plant running for 40 years at an average capacity factor of 85% in comparison with a similar plant with Chinese average efficiency (currently 29%).

** Direct emissions are zero for nuclear and renewables, but some CO_2 is emitted during construction, uranium mining etc. This makes a direct comparison problematic. A recent estimate for nuclear that includes these factors gives an emissions figure of 16g/kWh (Sustainable Development Commission, 2006).

Source: Authors' calculations based on (International Energy Agency, 2006a) and other sources.

It is difficult to provide a general guide to the costs of reducing carbon emissions from coal combustion. Some actual technology costs are given in the next section of this report. The main issue is that costs are location-specific and some (such as the costs of carbon capture technology) are subject to great uncertainty. As a general rule, the costs of reducing carbon dioxide emissions from coal-burning increase as emissions are progressively reduced. Incremental improvements to existing facilities will often pay for themselves through savings in fuel costs. However, increasing the average efficiency of Chinese power plants to the world average (see Table 3) would be more costly. It could be achieved through the retirement of smaller plants, upgrading operations and maintenance (O&M) practices at existing plants and substantial investment in new more efficient plants. In many cases the economic rationale for these measures is strong but barriers such as lack of finance or managerial autonomy can prevent their implementation.

For some advanced cleaner coal technologies, there is also an economic rationale but gains in efficiency (and reductions in running costs) may be outweighed by high investment costs and risks of newer technology. For carbon capture and storage, the economic rationale simply does not exist at present because investment costs are likely to be high, but are also very uncertain. A high price for carbon – for example in an emissions trading scheme – would be a necessary (but perhaps not sufficient) condition for these barriers to be overcome (Watson, 2006).

4. Cleaner Coal Technologies in Detail

This section assesses clean coal technologies in more detail. It provides an overview of the wide variety of technologies that can be included under a ‘cleaner coal’ heading, with a primary emphasis on those that can reduce carbon emissions. As the previous section shows, ‘cleaner coal technology’ encompasses a range of technologies which cover the preparation of coal (e.g. washing and briquetting), its combustion (e.g. fluidised bed boilers and gasification), the clean-up of waste gases (e.g. flue gas desulphurisation or FGD, denitrification and ultimately carbon capture and storage). It also includes incremental hardware and software measures that can improve the overall efficiency of coal use, particularly the thermal efficiency of boilers and power plants. Software measures include better maintenance and management of facilities, and the use of more sophisticated control and monitoring systems.

Many definitions of cleaner coal technology in OECD countries concentrate on new combustion and clean-up technologies, particularly those that can be deployed in the power generation industry. This is because many of the more incremental improvements that could benefit developing countries have already been implemented. There is large scope in developing countries for efficiency improvements across many industrial sectors. These might include the deployment of modern industrial boilers and coal gasifiers (e.g. to manufacture chemicals), a greater emphasis on coal washing and preparation (e.g. to reduce ash content before combustion) and better management and maintenance. Table 4 gives an illustration of this ‘efficiency gap’ with reference to the steel, cement and ammonia industries. Coal is a major energy source for these industries, particularly in large developing countries. Whilst the closure of this efficiency gap will require major investment in many cases, some cost effective improvements can be made through more incremental improvements to existing equipment (Watson and Liu, 2002).

Table 4. Energy intensities of industrial processes in different countries compared to the most efficient country (index: 100 = most efficient)

	Steel	**Cement**	**Ammonia**
Japan	100	100	-
Europe	110	120	100
United States	120	145	105
China	150	160	133
India	150	135	120
Best available technology	75	90	60

Source: (International Energy Agency, 2006b: 238).

Cleaner coal technologies also include a range of technologies that are not designed to reduce carbon emissions, but were developed to mitigate other environmental impacts of coal use. Examples include low NO_x burners, electrostatic precipitators (to reduce particulate emissions), flue gas desulpurisation equipment (which can reduce SO_2 emissions from power plants by around 90%) and fluidised bed boilers (which can help control both NO_x and SO_2 emissions). Many of these technologies have a neutral impact on carbon emissions, though some – particularly flue gas desulphurisation – increase emissions because they consume significant amounts of energy and therefore reduce the efficiency of plants at which they are installed.

The remainder of this section focuses on newer technologies that are designed to reduce carbon emissions significantly. They include more efficient combustion technologies (supercritical boilers), gasification technologies for power plants and carbon capture and storage technologies that could achieve emissions reductions of up to 90%.

Supercritical pulverised fuel technology

Supercritical variants of the pulverised fuel coal-fired technology were first developed in the USA during the 1960s. The aim was to increase plant thermal efficiency through the use of advanced materials so that the plant could operate with higher steam temperatures and pressures. Typical subcritical plants have steam pressures of 180bar and temperatures of 550°C.

Although many of the early supercritical stations were plagued by reliability problems, the technology is now considered to be commercially mature. There are now several hundred supercritical units in operation world-wide, most of which are located in a small number of countries. During the 1960s and 1970s, a large number were constructed in the USA. More recently, activity has been focused in Denmark, Japan, South Korea, Germany and Russia. In many cases, thermal efficiencies of over 40% have been achieved. According to one source, over 85% of new coal-fired capacity that was commissioned between 1997 and 2000 used supercritical technology (Department of Trade and Industry, 2003b). Since 2000, the proportion has almost certainly been lower than this. Developing countries such as China have started to install supercritical units, but most new plants still use subcritical technology.

One of the most advanced plants - unit 3 at the Aalborg power plant in Denmark - has a thermal efficiency of 47%, a 96% SO_2 removal rate and an 80% NO_X reduction rate (Modern Power Systems, 1998). This has been achieved by increasing the steam pressure to 285bar and the temperature to 580°C. The exceptional performance of this particular plant is largely due to the use of cold seawater in the condenser. An equivalent plant at an inland location in the UK would operate with a maximum efficiency of 44-45%.

A number of R&D initiatives are underway to improve further on this performance - and to move towards ‘ultra-supercritical’ steam conditions. A consortium of European manufacturers and utilities has been involved in the AD700 project funded by the European Commission since 1997 under its Framework R&D Programmes. The goals of AD700 are to develop and demonstrate a 50-55% efficient coal-fired plant with steam pressure of 300bar and temperature of 700°C (Advanced Power Generation Technology Forum, 2004). Whilst initial materials development phases of the project were completed, plans for a component test facility were scaled back. The main reason was a change of direction in the Commission’s 6th Framework Programme which commenced in 2002 (Kjaer, Bugge et al., 2004). This includes major activities in carbon capture and storage, but much less than previously on cleaner coal combustion technologies. As a result, firm plans for a full scale demonstration of the AD700 plant have not yet emerged, though the consortium hopes to secure funding from the current 7th Framework Programme to pursue this in combination with carbon capture and storage.

Despite its technical and environmental advantages, there has historically been a perception that supercritical technology is both expensive and unreliable. Although this perception is largely based on the poor reliability and inflexibility of many early supercritical units (especially in the USA), it affected the investment decisions of some power companies for many years afterwards. More recent experience shows that supercritical capital costs are similar to those of traditional subcritical coal-fired units (US Department of Energy, 1999). The recent Energy Review report published in the UK gives a range of £882-918/kW (approx $1750-$1800/kW) for a new supercritical plant including FGD (Department of Trade and Industry, 2006). Whilst this range is typical for UK deployment, costs in developing countries can be lower. The extent of this depends on a number of factors. For example, using lots of imported equipment from developed countries will put upward pressure on costs whilst the use of parts and labour within the country where the plant is being built will tend to lower costs.

Future developments of the kind envisaged in the European AD700 project might put upward pressure on capital costs. This is due to the need for advanced materials to allow increases in boiler temperature and pressure (McMullan, Williams et al., 2001). If they occur, such increases would mirror similar increases in coal-fired power plant costs in response to environmental regulations implemented in the 1970s (Joskow and Rose, 1983). However, these increases will be at least partly offset by lower running costs due to increased efficiency.

Pressurised fluidised bed combustion

Fluidised bed technology has been commercially available since the early 1980s, and has been used for some small coal-fired power plants in different countries. This technology has several advantages over the traditional coal-fired alternative, including an ability to remove sulphur during combustion and a low combustion temperature to limit NO_X emissions. As a result, it was successfully sold in niche markets in the USA and Europe during the 1980s and early 1990s (Watson, 1997; Banales-Lopez and Norberg-Bohm, 2002). Disadvantages include small unit sizes (<200MW in most cases) and thermal efficiency that is no higher than pulverised fuel plant.

Pressurised Fluidised Bed Combustion (PFBC), which was first developed in the UK, has the potential to address both of these shortcomings. The use of a pressurised steam boiler and a small gas turbine to generate supplementary power allows coal to be burned with a thermal efficiency of over 40%. This variant has been demonstrated at seven locations around the world (Watson, 2005). All but one of these plants were supplied or licensed by a single manufacturer - ABB Carbon of Sweden. The exception is the Osaki plant in Japan which was supplied by Hitachi. Most - if not all - were supported by government initiatives such as the EU Framework Programmes, the US Cleaner Coal Programme and Japanese government R&D programmes.

Capital cost estimates for existing PFBC plants are extremely hard to find, a problem which is probably exacerbated by the presence of a dominant supplier. Available figures suggest that demonstration plants have been much more expensive than standard coal-fired technology. Capital costs were $1900-$3200/kW in 1992 dollars. Whilst high costs are a common issue for demonstration plants, there is little further commercial experience so it is difficult to estimate the costs of a fully commercial plant.

As would be expected for such demonstration projects, reliability has not been very high in some cases. Nevertheless, PFBC technology appears to have some significant environmental advantages over conventional subcritical steam boiler technology. Sulphur dioxide emissions are similar to, or better than, many traditional power plants with Flue Gas Desulphurisation systems fitted. In all cases, PFBC NO_X emissions show a large improvement over conventional plants. However, the experience to date suggests that PFBC plants are no more efficient than those which use traditional pulverised fuel technology. Although part of this poor performance is due to the use of old steam turbines with new PFBC boilers, the 42% efficiency that was often quoted by ABB Carbon has not yet been achieved.

In recent years, interest in PFBC technology has receded - partly due to the perceived superiority of competing technologies such as IGCC and supercritical PF. ABB Carbon abandoned its PFBC technology in 2000/2001 as a result of poor commercial prospects and corporate restructuring. The ownership of this technology now resides with either Alstom or Siemens, each of which has inherited parts of ABB’s business in Sweden. In the USA, a 240MW demonstration PFBC power plant was due to be built at McIntosh power plant in Florida under the federal cleaner coal technology programme. However, this was withdrawn from the programme several years ago (US Department of Energy, 2003).

Integrated gasification combined cycle (IGCC)

The Integrated Gasification Combined Cycle (IGCC) is an outgrowth of the gas-fired Combined Cycle Gas Turbine (CCGT), the technology which has dominated global power plant orders in recent years. The basic difference between these two technologies stems from the presence of a gasifier and gas clean up equipment in an IGCC. This allows it to burn synthetic gas (or syngas) produced from coal or another fuel (e.g. heavy oil residues or biomass) instead of natural gas. Although the first coal-fired IGCC plant went into operation twenty years ago, this technology is still in its demonstration phase.

Coal-fired IGCCs were constructed at five sites in the USA and Europe in the 1990s (Watson, 2005). All have been supported by public funding - in this case from EU Framework Programmes and the US Clean Coal Programme. The capital cost of these plants varied widely, from $1670-$3360/kW (in the money of the day). As with the PFBC demonstrations, the fact that these plants were far more expensive to build than standard coal plants is not surprising. However, most studies still expect a commercial IGCC plant to have higher capital costs than a supercritical plant of the same size. For example, the UK’s most recent assessment estimates the difference to be between $200 and $400/kW (Department of Trade and Industry, 2006). A number of other plants are in operation that burn other gasified fuels (e.g. oil residues and asphalt), but these are not covered in this report.

One of the key issues to be resolved before IGCC technology can be offered commercially is reliability. Availability[8] figures show some evidence of improvement during demonstration

[8] Availability is defined as the amount of time that a power plant is able to produce power in a given period divided by the total amount of time in that period.

programmes. For example, the Wabash River plant in the US improved from an initial availability of 40% in 1995 to between 65% and 75% during 1997. Similarly, Tampa Electric's plant overall availability improved from 33% in 1996 to around 80% in its final three years of operation from 1999-2001 (Tampa Electric Company, 2002). At Buggenum in Holland, availability has improved from initial low levels, and was quoted at 65-75% in 2002 and 2003. By contrast, the worst performer was the Pinon Pine plant in the USA which has now closed. Its coal gasification system was only operated for a total of 128 hours.

According to an assessment by the Electric Power Research Institute (Holt, 2003), none of the demonstration plants have achieved their target availability level of 85%. This assessment suggests that the main challenges for IGCC include system integration (getting a combined cycle plant and a gasification plant to work together), gas clean-up (making synthetic gas clean enough for modern gas turbines), and gas turbine reliability (particularly the case for European plants that used Siemens gas turbines).

In contrast to reliability, the environmental performance of IGCC technology has lived up to expectations (Watson, 2005). In terms of thermal efficiency, sulphur dioxide and nitrogen oxides IGCC performance is at least as good as that of other cleaner coal options. Thermal efficiencies of between 39-43% have been achieved. The US plants have lower thermal efficiencies than those in Europe. In the case of Wabash River, this can be explained by the fact that an old steam turbine has been repowered with a new gasifier and gas turbine.

Since the construction of these five demonstration plants, no further coal-fired IGCC plants have been completed. The US Department of Energy has tried for several years to persuade utilities and governments in China and India to purchase IGCC units based on demonstrated designs. The underlying rationale is to provide US taxpayers with some return on the investments they have made in the US R&D programme. These efforts have not yielded any concrete results so far. However, at least two US utilities (Cinergy and American Electric Power) have announced their intention to construct new coal-fired IGCC plants in the next few years. Two further IGCC plants have been given the go-ahead under the clean coal programme's successor, President Bush's Clean Coal Power Initiative. Provisions for subsidy of such new plants were included in the recently passed US Energy Policy Act of 2005, making the chances of implementation high (Neff, 2005). In Japan, concrete IGCC development plans are also underway. A new 250MW demonstration plant is due to begin operating in mid-2007 (Jaeger, 2006). It is being developed by a consortium of Japanese utilities with support from the Japanese government.

Carbon capture and storage (CCS) technologies

The usual argument made about CCS is that all of the main technological elements are well known including carbon dioxide capture, transport by long distance pipeline, and injection and storage in geological formations. However, full scale systems that are capable of capturing and storing 80-90% of CO_2 emissions from a typical coal-fired power plant have not yet been implemented. Therefore, the main challenge is to build an integrated CCS system in conjunction with a full-scale power plant (Department of Trade and Industry, 2006).

Even if full-scale CCS systems were available today, cost would be a major barrier to deployment. The addition of carbon capture equipment to a power plant and the construction of transport and storage infrastructure do not come cheap. All studies of CCS economics point to a considerable cost premium to account for this. Furthermore, the costs given in these studies are subject to significant uncertainty due to the lack of full-scale experience. Capital costs of plants are expected to be several hundred dollars higher per kW installed than the costs of equivalent plants without CCS. For example, recent figures from an IPCC special report on CCS show that carbon capture would increase the costs of a coal plant between $500 and $800/kW (an increase of 35-60%) depending on the technology being used (Intergovernmental Panel on Climate Change, 2005). Furthermore, CCS brings with it an energy penalty which lowers plant efficiency and increases fuel costs.

There are also a number of other challenges and uncertainties. For example, the storage of CO_2 underneath the seabed is subject to international conventions such as the international London Convention and OSPAR which applies to the North Sea[9]. These are in the process of being modified to accommodate CCS. There are also uncertainties about long-term storage and the potential for leaks over the timescales required. This, in turn, is likely to affect public acceptance (Shackley, McLachlan et al., 2004).

From a technical perspective, there are challenges that go beyond system integration and scale-up. Perhaps the most important is that some of the power generation technologies that will be incorporated into future CCS systems such as IGCC are not fully commercialised (see above).

Post-combustion carbon capture

As its name implies, post-combustion carbon capture involves the removal of CO_2 from a power plant's flue gas. It is usually associated with the use of conventional pulverised fuel plants. The most common technology proposed for post-combustion carbon capture within a pulverised fuel plant is the use of amine scrubbers. These been used for decades in the oil and chemical industries – mainly for removing hydrogen sulphide and CO_2 from waste gases. It has been used to remove 150 tonnes per day of CO_2 in the Warrior Run power plant in the USA at a cost of ~$100/tonne (IEA Greenhouse Gas R&D Programme, 2001). It is also being used in the world's largest saline aquifer CO_2 storage project – in the Sleipner West oil field. So far, post-combustion carbon capture has not been implemented on a scale necessary to remove CO_2 from a typical coal-fired power station. According to one recent assessment (Department of Trade and Industry, 2003a), the largest scheme to date is in operation in California. This captures 800 tonnes per day of CO_2. A 500MW coal-fired power station would require a 'capture capacity' that is ten times bigger than this.

A number of plans for full-scale demonstration of post-combustion carbon capture are under consideration in industrialised countries. For example, an engineering study that is being carried out by Scottish and Southern Energy in the UK with Doosan Babcock and Siemens. This would involve retrofitting an existing 500MW coal-fired unit with a new capture ready supercritical boiler. The installation of carbon capture equipment would take place at a later date.

[9] The OSPAR convention, formally known as the Convention for the Protection of the Marine Environment of the North-East Atlantic, entered into force in 1998.

Oxyfuel combustion is more speculative and experimental approach to post-combustion carbon capture. It involves burning the coal in an oxygen and CO_2 rich mixture rather than air. This produces a waste gas stream rich in CO_2 from which the CO_2 much easier to capture. Its main drawback is the need for an expensive, energy intensive air separation unit. There are proposals for oxyfuel schemes that do not require such a unit, but these are radical and untested.

Pre-combustion carbon capture

The most common route that is suggested for pre-combustion carbon capture from coal is the use of Integrated Gasification Combined Cycle (IGCC) technology (see above). Pre-combustion CO_2 capture from an IGCC plant can be achieved by removing the CO_2 from the syngas within the gasifier. The process for removing carbon dioxide in this way is already in use – for example, the Great Plains synfuels plant in the USA does this on a scale suitable for power generation applications. However, the technical advances necessary to allow hydrogen to be burned in a gas turbine have not yet been made. Whilst General Electric has one gas turbine plant in Germany that burns syngas containing 60% hydrogen, pure hydrogen combustion presents challenges for materials, emissions control etc. An alternative to this would be to use the hydrogen directly in a fuel cell.

Although pre-combustion carbon capture in a power station has yet to be demonstrated, a number of government and industry R&D initiatives are underway. Perhaps the most notable is the US Department of Energy’s Futuregen project (US Department of Energy, 2004). This $1bn project aims to design, construct and test a 275MW IGCC electricity and hydrogen plant. A shortlist of four sites for Futuregen has recently been announced. The plant was originally scheduled to be in operation by 2011, though this is now subject to delay due to difficulties in securing funding from Congress (Platts, 2005).

Transport and storage of CO_2

There are a number of established options for transporting carbon dioxide from a coal-fired power station to a storage site. Pipelines to transport CO_2 are already in use in the USA – in oilfields and at natural gas processing plants. Around 30 million tonnes of CO_2 is transported in the US in this way each year, and the longest pipeline is over 400 miles long (IEA Greenhouse Gas R&D Programme, 2001). The transport of CO_2 in this way is cheaper than electricity transmission. Therefore, it makes economic sense to build coal-fired power stations near to load centres instead of locating them next to CO_2 storage sites. This may not, however, be acceptable to local populations due to concerns about environmental impacts and safety.

Tankers could be used as an alternative to pipelines, particularly for long distance transport. The tankers would be similar to those that transport liquefied natural gas. However, the liquefaction of the carbon dioxide would require a significant amount of additional energy.

The storage of carbon dioxide in depleted oil and gas fields is possible because these fields have remained sealed for long periods of time prior to extraction. Another advantage of these fields is that their geology is relatively well known. The IPCC special report on CCS estimates that the global capacity for this kind of storage could be 657-900 gigatonnes (Intergovernmental Panel on Climate Change, 2005).

In the short to medium term, CO_2 storage in depleted oil fields is thought to be a particularly attractive option for those countries with active oil and gas industries. This is due to the scope for enhanced oil recovery (EOR). An EOR process injects CO_2 into partially depleted fields to extract additional quantities of oil. The revenue gained from the sale of this additional oil might help to offset the costs of capture and storage. EOR is an established technology that has been implemented in a number of locations, particularly in North America where there are over 74 EOR projects (IEA Greenhouse Gas R&D Programme, 2001). The most well known of these is the Weyburn EOR project in Canada which takes CO_2 from a synfuels plant in North Dakota.

Deep saline aquifers are estimated to have the largest potential for geological carbon dioxide storage. They consist of large rock formations that contain salt water that is not suitable for drinking. CO_2 could be injected into these formations using similar techniques to those for EOR. The most appropriate aquifers are located beneath rock with low permeability to minimise CO_2 leakage. The global estimated capacity of saline aquifer storage from the IPCC gives a range of 1000-10,000 gigatonnes (Intergovernmental Panel on Climate Change, 2005).

One further geological storage option merits some attention - the use of difficult or un-mineable coal seams. These could be used to ‘fix’ CO_2 to unmined coal by an adsorption process. One possible advantage of this method is that this CO_2 would displace methane which could then be recovered and used. However, this could then generate more CO_2 which would then have to be dealt with. The global capacity for this form of storage is very uncertain - estimates range from 3 – 200 gigatonnes of CO_2 (Intergovernmental Panel on Climate Change, 2005).

5. Country Case Studies

China

Coal and the environment in China

As the largest coal producer and consumer in the world, China could be the largest and most important market for cleaner coal technologies. The severe environmental pollution derived from China's inefficient coal combustion and poor clean-up processes also provide a large scope for these technologies to be widely implemented in China. The global challenge of climate change has made this a more urgent requirement for China.

Coal accounts for more than 70% of indigenous primary energy production in China, largely due to China’s scarce oil and natural gas reserves. Coal also accounts for more than 60% of overall primary energy consumption in China, and will remain so for a foreseeable future. More than half of the coal is used in power generation and more than 40% is burned by direct combustion in the industrial boilers and households (Yu, Xiao et al., 2004). As this suggests, the power sector is not the only major coal consumer. Construction, metal and chemical engineering sectors consumed 12%, 9% and 6% of coal in 2002 respectively (Yu, Xiao et al., 2004). Overall coal accounts for 90% and 40% of the fuel used in industrial boilers and by households respectively.

Chinese coal comes from various sources and is generally of low quality. The average sulphur content of Chinese commercial coal is 1.01%, and average ash content is 23.85% (Yu, Xiao et al., 2004). However, only a small proportion of coal is washed before use. As a result, coal combustion is causing serious atmospheric pollution in China. Due to the poor performance of desulphurisation in China, 90% of national sulphur dioxide emissions come from the combustion of coal, and power generation accounts for 40% of the total. Acid rain caused by sulphur dioxide emissions is falling on one third of China's land area. In recent years, CO_2 emissions have become an important concern. China is likely to overtake the US and become the world's largest CO_2 emitter around 2010 (International Energy Agency, 2006b).

Chinese energy projections and cleaner coal technologies

The demand for coal in China has risen rapidly in recent years. Economic growth has averaged around 10% per year, and coal demand has increased rapidly too. Many projections for future coal demand growth show that increases will continue for the foreseeable future. To illustrate the potential impact of future growth on CO_2 emissions, and the scope for cleaner coal technologies to reduce these emissions, it is useful to focus on the power sector. This sector is expected to account for the majority of the growth in Chinese coal demand.

As Table 5 shows, there was 307GW of coal-fired capacity operating in 2004. Official data from China Electricity Council (CEC) indicates that China’s total generating capacity reached 508 GW in 2005, and increased to 622 GW in 2006[10]. Coal-fired capacity increased to 384 GW in 2005 and 484 GW within 2006. The size of the 2006 increase took many officials and independent observers by surprise – the increase is almost twice the power plant capacity in

[10] Report at http://www.cec.org.cn/news/showc.asp?id=92985

operation in California (McGregor, 2007). The International Energy Agency assumes that rapid growth will continue, albeit at a slower annual rate. This is even the case under the IEA's alternative policy scenario that assumes greater government efforts to limit rises in CO_2 emissions and therefore, lower growth of coal-fired plant.

Table 5. IEA projections of coal-fired generation and emissions in China (2004-2030)

	2004 actual	**2015**	**2030**
Reference Scenario			
Coal-fired capacity (GW)	307	688	1041
Coal-fired generation (TWh)	1739	3966	5980
Alternative Policy Scenario			
Coal-fired capacity (GW)	307	638	833
Coal generation (TWh)	1739	3666	4766

Source: (International Energy Agency, 2006b).

The growth expected by both IEA scenarios is higher than that assumed by analysis for China's own National Energy Strategy and Policy 2020 which was completed in 2004. This foresees total coal-fired capacity reaching 419GW by 2010 – a lower figure than the official total for 2006 (Yu, Xiao et al., 2004).

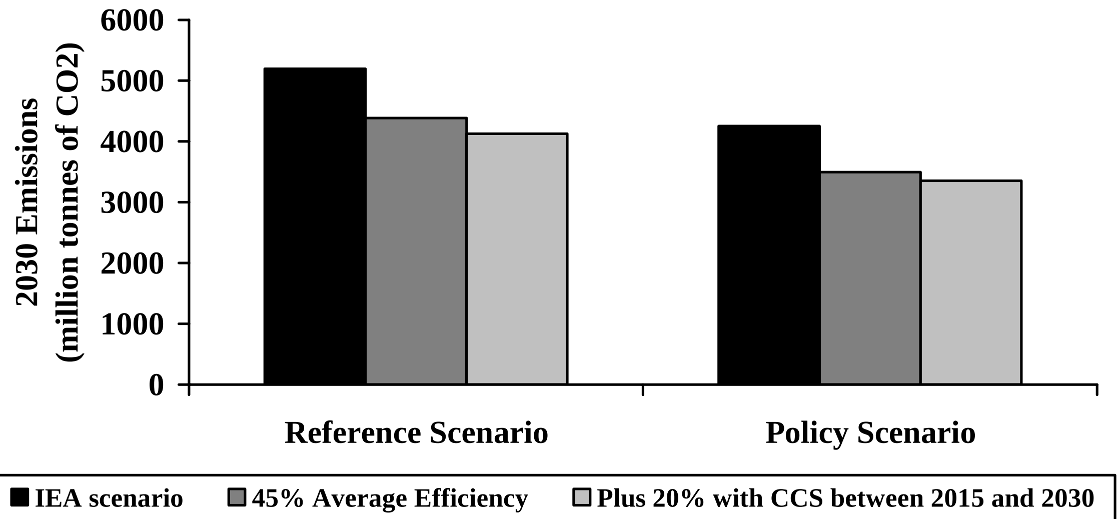
In both sets of projections, cleaner coal technologies are expected to play a modest role before 2020 or 2030. The IEA assumes a gradual increase in the use of supercritical technology world-wide in its reference scenario. This scenario also includes the construction of 144GW of IGCC capacity, half of which would be built in the United States. The impact on China of this technology within the scenario is unclear but is likely to be limited. Interestingly, the IEA assumes that carbon capture and storage will not be commercially attractive by 2030.

The IEA scenarios can be used to analyse the potential impact of accelerated cleaner coal technology deployment on power sector emissions[11]. To do this, the emissions factors that were given earlier in this report have been used (see Table 3 in section 3). According to the Agency data used in the World Energy Outlook (International Energy Agency, 2006b), the average efficiency of Chinese coal-fired plants in 2005 was 29%. Within the Outlook's reference scenario, this average efficiency is expected to rise to 38% by 2030. In the alternative policy scenario which leads to a reduction in the use of coal, less new coal-fired capacity is deployed and therefore average efficiency only reaches 37%.

[11] A similar exercise was carried out for the National Energy Policy strategy 2020 which gives cumulative reductions in coal demand, SO_2 and CO_2 largely from increased supercritical technology deployment. See Yu, Z., Y. Xiao, et al. (2004). Policy study on development and utilization of CCT.China National Energy Strategy and Policy 2020, Clean Coal Engineering & Research Center of Coal Industry and Institute of Engineering Thermophysics of Chinese Academy of Sciences.

It is possible to imagine a faster introduction of cleaner coal technologies than the World Energy Outlook envisages (see figure 2). For example, standards could be tightened and enforced so that the use of supercritical and IGCC technologies increased more quickly. In addition, older, less efficient plants could be retired earlier. If these measures were able to push average efficiency to 45% by 2030, the reduction in CO_2 emissions in that year would be 808 million tonnes in the reference scenario or 756 million tonnes in the policy scenario. Further reductions would be realised if carbon capture and storage technology were successfully commercialised. For example, if 20% of new Chinese coal-fired plants were fitted with this technology between 2015 and 2030, an additional 141-257 million tonnes of CO_2 would be saved annually by 2030 depending on the scenario. To put these figures into perspective, the UK's total net emissions in 2006 were 561 million tonnes of CO_2. This was around 2% of the global total.

Figure 2: Impact of accelerated deployment of cleaner coal technologies on coal-fired power plant emissions in China (2030)



Source: Calculations based on figures used in (International Energy Agency, 2006b).

Implementing cleaner coal technologies in China

Some of the most cost-effective options to combat CO_2 emissions for China are to reduce coal consumption through improved coal combustion efficiency. In the longer term CO_2 emissions from coal combustion could be reduced substantially through carbon capture and storage (CCS). But the deployment of cleaner coal technologies in China – particularly more advanced technologies - is constrained by high costs and a lack of policy support.

Short Term

In the short term, Chinese firms have the capacity to build on existing competencies in a number of cleaner coal technologies including coal washing, various efficiency improvements and small circulating fluidised bed boilers. Many of these technologies are now well established and commercialised in China, though some do not have a direct impact on carbon emissions.

Basic coal washing technologies are well established in China. In 1997, there were over 1500 coal preparation plants in operation with enough capacity to wash a third of China's coal output (Cheng, 1998)[12]. The main function of the washing plants is to reduce the amount of ash in the raw coal to facilitate combustion and to increase the energy content as well as to reduce the sulphur content of the coal when it is burned. In addition, more modern washing processes are being developed to decrease the amount of water required and to increase the effectiveness of ash and sulphur removal.

Incremental improvements to the performance of existing power stations, industrial boilers and other facilities are perhaps the most important cleaner coal technologies for the short term. Such improvements can lead to a significant reduction in emissions from coal-fired facilities. For example, Chinese fossil-fuel electric power plants have historically had thermal efficiencies that are significantly lower than typical figures for plants in more industrialised countries. Table 6 shows some comparative date from 1996. More recent figures show that little progress has been made since then. In 2005, coal-fired power plants consumed 370g of coal per kWh of electricity produced (Zhang and Zhao, 2006). The consumption of larger units is better than this average. For example, 300MW units consume approximately 342g/kWh. The most efficient supercritical units which are larger still operate as well as a typical plant in an OECD country, with coal consumption of 321g/kWh.

Table 6. Energy Consumption for Key Industrial Products in China, 1996

Industrial Product	**Energy Consumption**		
	China	**OECD**	**Difference**
Steel (kg coal equiv./tonne)	1392	629	221%
Synthetic Ammonium (kg coal equiv./tonne)	2062	930	222%
Cement (kg coal equiv./tonne)	174	113	154%
Coal Fired Electricity (g coal /kWh)	371	325	114%

Source: (Yu, 1999)

The Chinese average is affected by the large number of small power plants in use. In 2005, only 333 of China's 6911 coal-fired units had capacities of at least 300MW. Many of the remainder have capacities of less than 100MW (Zhang and Zhao, 2006). There is therefore pressure from central government in particular to phase out the use of these smaller, inefficient units. The lower average efficiency in China also reflects the use of older turbine designs, the lack of advanced control systems and a poor level of preventative maintenance (Watson, Oldham et al., 2000). In view of this, there have been some international programmes to try and improve operations and maintenance practices such as missions of engineers from OECD countries under the auspices of the International Energy Agency.

[12] In practice, these plants are not operated at full capacity - whilst the total washing capacity was 480 million tonnes in 1997, only 340 million tonnes were processed.

Outside the electric power industry, much larger ‘efficiency gaps’ have been identified in Chinese industrial facilities. During the late 1990s, it was observed that the average industrial boiler in China was operating at an efficiency of 65% whilst boilers in OECD countries have efficiencies of over 80% (Jin and Liu, 1998). Chinese cement kilns consumed 53% more coal and China’s steel mills consumed over twice as much coal than their OECD counterparts to produce the same quantity of output. Some comparisons with typical installations in OECD countries at that time are shown in Table 6. More recent figures indicate that significant improvements in energy efficiency have been made in some cases. In 2004, large and medium sized steel mills consumed on 705 kg of coal per tonne of steel (only 7% more than in Japan) whilst smaller mills consumed 1045kg/tonne (Wang, Wang et al., 2007).

China also has considerable capability in designing and manufacturing circulating fluidised bed boilers. Chinese engineers started the design of small fluidised bed since 1960s. This type of boiler has particular advantages in China, as it is suitable for indigenous low quality coal and desulphurisation during combustion. However, it does not offer any efficiency advantages over a standard boiler design. After decades of development, these boilers have been applied widely in Chinese industry. In common with world-wide developments, these designs have not yet been scaled up to the size required for a full-scale power plant. Furthermore, Chinese designs did not advance as far as international technology with respect to sulphur removal. Therefore foreign fluidised bed technology has been sought. After a few demonstration projects in the 1990s, Chinese firms have now started to produce 200MW fluidised bed boilers using their own designs and are developing larger unit sizes (see below).

Medium Term

A number of cleaner coal technologies are being promoted by the Chinese government through environmental regulations. These include larger scale fluidised bed boilers, supercritical boilers for coal fired power plants, flue gas desulphurisation (FGD) and coal gasification. Despite progress, the implementation of these technologies in China still lags behind the situation in OECD countries. Therefore, technology transfer will be important in accelerating their deployment in China in the medium term.

Due to its inherent advantages of using low quality coal and desulphurisation, large scale fluidised bed boilers could be particularly valuable for China. In July 2006, the first large scale (210MW) boiler of this type with independent intellectual property rights started commercial operation in Jiangxi province. In the same year, two 300 MW circulating fluidised bed boilers produced by Chinese manufacturers were installed in Hebei province. The Chinese government is now promoting the development of 600 MW units (National People's Congress, 2006). It should be emphasised that none of these units will have better efficiencies than standard boiler technologies. The pressurised variants of this technology that have been developed in industrialised countries to increase efficiency (and thereby reduce carbon emissions) have been recently been abandoned (see Section 3 of this paper).

Supercritical boilers use higher steam temperatures and pressures to increase the thermal efficiency of coal-fired power plants. Despite early unreliable experiences, the designs have been largely improved. As outlined in Section 3, this is now a widely established practice in many countries including China. Supercritical boilers are regularly installed in new power stations in

China to replace the outdated small conventional coal-fired power plants. Some experts argue that supercritical and ultra supercritical boilers will be the most important option for power generation for China (Yu, Xiao et al., 2004) for the foreseeable future. By end of 2001, China had 7.8GW supercritical power plant, less than 3% of the coal fired generation capacity. Another 5.16 GW was added by the end of 2004. According to some reports, this trend has now accelerated. Equipment manufacturing firms are now developing supercritical units with an increasing amount of independence from foreign technology suppliers (Yu, Xiao et al., 2004). In 2006, the first two 1000 MW ultra supercritical boilers produced by Chinese manufacturers started commercial operation in a new power plant in Zhejiang province. Including this one, 22 GW of ultra supercritical boilers manufactured by Chinese firms are to be installed in China within next few years. Unlike the power sector, other industries are much more reluctant to introduce these technologies due to high costs.

End of pipe technologies to remove particulates, SO_2 and NO_x are becoming standard for new-build power plants in China, though implementation of these measures is still unsatisfactory. Many of the boilers in power plants have low NO_x combustors. The new large power plants are equipped with electrostatic precipitators to remove soot from the flue gas (Watson and Liu, 2002). After years of upgrading, 86% of Chinese power plants had installed electrostatic precipitators in 2001, compared with 60% in 1996 (Yu, Xiao et al., 2004). Low NO_x combustors are now compulsory for new power plants larger than 300MW. The existing power plants without it will be upgraded or replaced gradually. Unlike these measures, FGD has not yet been widely deployed in China. In 2000, only 3% of Chinese coal fired power plants (6.95 GW) had installed FGD (Yu, Xiao et al., 2004)[13]. FGD is compulsory in China for all the new power plants using coal with more than 1% sulphur content. Power plants larger than 300MW will tend to use Wet FGD (limestone-gypsum) or more advanced FGD technologies, while cheaper options such as rotary spraying or in-bed calcium injection is allowed for smaller power plants. Existing large power plants are also required to add FGD equipment. However, the enforcement of these regulations remains patchy at best. Even when FGD projects under construction are completed, only 5% of China's coal-fired plants will include this technology (Massachusetts Institute of Technology, 2007). A major problem remains the high cost, especially of imported equipment. Some efforts to transfer foreign technologies to China have been made under the Japanese Green Aid Plan, but high costs meant that initial demonstration projects have not been replicated (Evans, 1999b).

As one of the basic coal conversion technologies, coal gasification is widely used in China, but most installations use outdated designs. In general, these coal gasifiers are small and inefficient and used for industrial processes such as fertiliser and chemical production. Cleaner and more advanced gasifier designs have been introduced to China by foreign firms such as Shell (Watson, Oldham et al., 2000). These are sometimes installed as retrofits to existing gasification facilities to reduce emissions through increases in efficiency. Shell has now licensed 15 gasification plants throughout China, the first of which was built by a 50:50 joint venture between Shell and Chinese State oil company Sinopec (Chhoa, 2006). It entered full operation in 2006.

[13] A more recent study by MIT gives a lower figure of 5.3GW. See Massachusetts Institute of Technology (2007). The Future of Coal: Options for a Carbon Constrained World. Boston, MA, USA, MIT.

Long Term
More advanced clean coal technologies such as Integrated Gasification Combined Cycle (IGCC), coal liquefaction and carbon capture and storage (CCS) are still relatively immature even in OECD countries. In need of significant improvements, these technologies have long term prospects in China.

China is now becoming active in the development of IGCC technology, with several demonstration projects under construction or in planning. China approved the first IGCC demonstration project to be constructed in Yantai in 1999. When finished, it will have a capacity of 300-400MW. This project was, however, delayed by several years due to a lack of finance. Numerous design studies were undertaken with the support of international aid agencies but progress to actual implementation has been slow (Watson, Oldham et al., 2000). There are now reports that construction started in 2004 and it is expected to be completed in 2010. Independently of this, China Hua Neng Group started working on another 250MW IGCC demonstration project in Tianjin using a design developed by the Thermal Power Research Institute (TPRI). The first phase with targets of near zero emissions of SO_2, NO_x and particulates is expected to operating in 2010. In its second phase which is due to be completed by 2015, the project has the ambitious target of near zero emissions of CO_2 and the production of hydrogen.

Currently there are some limited moves to explore the potential of carbon capture and storage (CCS) technologies in China. CCS technology is integrated into the National Medium- and Long-term Science and Technology Development Plan towards 2020. In principle, there is capacity for storage of large amounts of carbon dioxide in saline aquifers or depleted hydrocarbon fields. However, many of these are remote, and are not close to the majority of large point sources such as power plants (Massachusetts Institute of Technology, 2007). A feasibility analysis of the potential and scope for CCS is still needed before the extent of accessible storage is known with any certainty.

Nevertheless, several Enhanced Oil Recovery (EOR) projects have already been implemented in Chinese oil fields. These are being pursued for economic reasons rather than any strategy to explore CO_2 storage for climate change mitigation. In addition to this, there are several other early signs of Chinese interest in CCS technologies. China and several other developing countries are involved in the work of the Carbon Sequestration Leadership Forum (CSLF). One Chinese utility (the China Hua Neng Group) has joined the Futuregen Alliance which plans to build an IGCC plant with CCS by 2012 (see Section 3 of this report). The first phase of a full-scale demonstration of CCS technology within China has also been funded (see Box).

Box. The near-Zero Emissions Coal (nZEC) Project

Perhaps the most concrete move towards demonstration of CCS in China so far is the near-Zero Emissions Coal (nZEC) project, which is part of the EU-China Partnership on Climate Change announced at the EU-China Summit in September 2005. The project is planned in three phases following agreements signed by the Chinese Ministry of Science and Technology, the UK Government, and the European Commission. The UK government is leading the first phase with £3.5m of funding, which is a three year feasibility study. This study will examine various technological options to capture CO_2 emissions from power generation and explore the potential for geological storage in China. The ultimate target is to demonstrate near zero emission coal fired power generation at commercial scale by 2020. Progress in implementing the first phase is slow so far, whilst details of funding for the second and third phases have yet to be revealed.

Overall, the high costs and technical uncertainties of CCS technologies mean that it is unlikely to be considered for new power plants. However, developed countries such as the UK are hoping to persuade China to build ‘capture ready’ plants which can have CCS technology added to them relatively easily in the future (Parliamentary Office of Science and Technology, 2005).

Barriers to cleaner coal technologies in China

Despite China’s huge potential demand for cleaner coal technologies, the large scale deployment of these technologies faces critical barriers in areas such as institutions, regulations and technology. China has no specific department or administration in charge of the development of cleaner coal technologies. Different institutions are responsible for the development of various technologies in mining, power generation and environment protection.

There is a particular tension between central government policy and local or regional implementation of policy. A significant proportion of Chinese coal-fired power plant development is out of the control of central government, and is not required by local government to conform to the most stringent environmental and technical standards. As MIT have observed in their recent study, this means that around 110,000MW of China’s existing coal-fired capacity is technically illegal (Massachusetts Institute of Technology, 2007). This approach – characterised by MIT as ‘self-help’ – is encouraged by rapid demand growth and a perception that central government approval is bureaucratic and adds to costs.

Furthermore, emissions monitoring and regulatory enforcement by local environmental protection agencies is weak. Protectionism and an emphasis on local economic stability and employment can mean that smaller, inefficient facilities are kept open or not upgraded (Watson and Liu, 2002). Without more stringent regulations and enforcement with respect to smaller facilities, environmental problems derived from coal consumption are unlikely to be tackled effectively, and the clean coal technologies deployed in the power sector can go no further than demonstration projects. For instance, the SO_2 emission fee in the Two Controlled Zones (which have the tightest regulations) is lower than the abatement cost to the industries – so there is no incentive to install sulphur control technologies. A recent MIT study also observed that local environmental protection agencies are seriously underfunded and therefore have an incentive to collect pollution fees from industry – instead of reducing pollution - to finance themselves (Massachusetts Institute of Technology, 2007).

Inefficiencies in China’s coal distribution system also create disincentives for investment. Most of the high quality coal with low sulphur content is consumed by the power plants where desulphurisation and cleaning-up processes are available, while cheaper low quality coal with high ash and sulphur contents is purchased by households and industries without much end of pipe treatment.

Research and large-scale deployment of some of the more advanced technologies is capital intensive and carries with it high risks. Financial support from the government is still insufficient and too intermittent to encourage firms to commit to these technologies. Some high profile projects such as the Yantai IGCC plant have been delayed for many years due to a lack of funding[14]. To promote large demonstration projects, the Chinese government would need to offer substantial incentives, possibly in conjunction with foreign finance and/or carbon credits from the CDM. However, it should be borne in mind that the CDM is unlikely to finance advanced cleaner coal technologies such as IGCC or CCS in the foreseeable future since many lower cost abatement opportunities are available such as efficiency improvements and renewable energy.

International technology transfer has large scope to help China to improve its cleaner coal technologies. Key technology developments in China such as fluidised bed boilers, efficient gasifiers, supercritical boilers and latterly IGCC have all occurred with some foreign technology. Many successful collaborations and transfers have been privately led without the involvement of governments.

For many years, various initiatives and programmes led by US, Japan, EU and other international parties like the World Bank have sought to accelerate the transfer of such technologies. However, the experience of these programmes has been mixed (Watson and Liu, 2002). Technology transfer beyond the installation of new equipment and some operator training has often not occurred due to a range of factors. These include concerns about intellectual property rights protection amongst international technology suppliers. But they also include poor design and implementation of programmes by governments and multilateral institutions.

[14] This point is also made by the recent MIT future of coal study: Ibid.

India

Coal and the environment in India

India is the world's second most populous country next to China and at current growth rates its population is predicted to equal that of China by 2030. Between 1990 and 2001 India's carbon emissions increased by a significant 61%, an increase second only to China's 111% increase in the same period (EIA, 2004; Ghosh, 2005). This rise in India's carbon emissions has been exacerbated by the low energy efficiency achieved by the country's coal-fired power plants (Ghosh, 2005). India's economic growth rate is approximately 1.5% below that of China and its electricity consumption per capita is only around a third of that observed in China (Massachusetts Institute of Technology, 2007). Nevertheless, India is putting in place policies to rapidly speed growth in the power sector, the vast majority of which will be met by coal fired generation. This highlights the importance of clean coal technologies in India if future CO_2 emissions are to be minimised. At the same time, there is a positive side to this in that, relative to China, India's early stage of growth suggests greater potential to implement technological and institutional improvements before the greatest level of growth occurs in India (Massachusetts Institute of Technology, 2007).

India is the world's third largest coal producer after China and the USA, accounting for 8% of global production. It has 10% of the worlds proven reserves of coal, the fourth largest after the USA, Russian Federation and China (BP, 2006). It is also the world's eighth largest importer of coal (IEA, 2000). Reserves of coal in India are high relative to current production levels with a reserves-to-production, R/P, ratio of 217. This compares favourably with India's R/P for crude oil (20.7) and natural gas (36.2) (BP, 2006).

One limitation of Indian coal is its high ash content (around 50%) and general variable quality. This adds additional energy requirements in terms of cleaning and transporting coal for power generation and can cause problems for its use with advanced clean coal technologies such as IGCC. India has also experienced problems related to inefficiencies in the coal supply chain including bottle necks in railway transportation over long distances (Shackley, 2007). This led to a rapid expansion in natural gas based power generation capacity in recent decades. In recent years, the increasing volatility in the price of gas has caused concern due to the limited availability of domestic gas reserves (Ghosh, 2005) and led to a renewed emphasis on coal based power production (Shackley, 2007). This emphasis on coal is unlikely to diminish in the medium to long term in India.

Whilst coal has other industrial applications in India, most significantly in fertilizer production, the majority, around two thirds, is used in power generation. In 1998, coal met around 60% of commercial energy needs with around 70% of total electricity generated coming from coal (TERI, 1998). This share is set to rise steadily over the next few decades with significant aggregate increases in coal fired power generation resulting from the rapid increase in economic activity in India. This sustained dominance of coal as the predominant source of energy generation in India in the foreseeable future will result from both the abundant availability of coal in the country and a combination of economic and security drivers. This trend highlights a need to develop a pattern of coal usage that is both economically efficient and environmentally sustainable (Ghosh, 2005). In light of this, clean coal technologies clearly have an integral part to play in reducing future CO_2 emissions in India.

Indian energy projections and cleaner coal technologies

Most projections expect Indian coal demand to rise significantly over the short to medium term. The International Energy Agency's reference scenario projects that India's demand for coal will double by 2030 (International Energy Agency, 2006b). Another recent study by MIT suggests that coal use in India could equal current consumption in the US by around 2020 and equal the current level in China by around 2030 (Massachusetts Institute of Technology, 2007)

As with the China case study in this report, it is useful to examine the impact of this expected growth on CO_2 emission by focusing on the electricity sector. The capacity of coal-fired power plants in India is currently around 70GW[15], whilst the total installed capacity is 128GW. Over the past 25 years, electricity generation has risen by an average of 7% per year (Planning Commission, 2006). Around 2GW of new coal-fired capacity was added in 2006 (out of a total of 5GW) (Ministry of Power, 2007). Table 7 illustrates the IEA's projections for coal fired power generation and associated emissions for heat and power. It compares these with an alternative policy scenario representing projections under increased government efforts to realise efficiency gains.

Table 7. IEA projections of coal-fired generation and emissions in India (2004-2030)

	2004 actual	2015	2030
Reference Scenario			
Coal-fired capacity (GW)	72	128	251
Coal-fired generation (TWh)	461	836	1631
Alternative Policy Scenario			
Coal-fired capacity (GW)	72	117	191
Coal generation (TWh)	461	765	1242

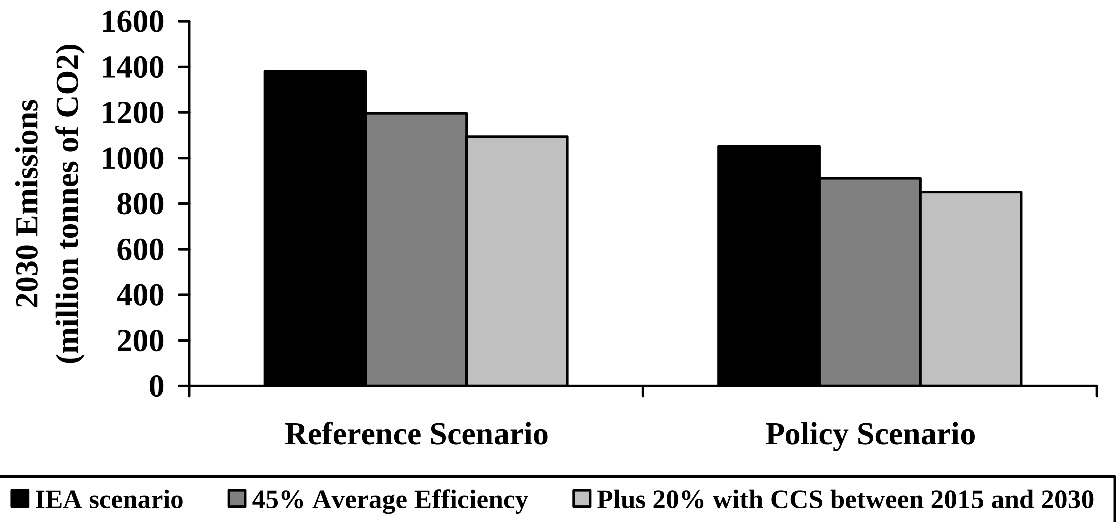
Source: (International Energy Agency, 2006b).

The IEA's forecasts are on the low side of those contained in recent scenarios from the Indian Planning Commission (Planning Commission, 2006). These scenarios see coal-fired capacity reaching at least 270GW by 2031/32 – and imply that one new 1GW coal-based power plant will need to be built every two weeks to a month from now until that date (Shackley, 2007). The Planning Commission estimates that the current average generating efficiency for coal fired power generation in India is around 30.5% (Planning Commission, 2006, p.vii). Other authors cite a fleet efficiency of 31.6% (Sivaramakrishnan and Siddiqi, 1997; Ghosh, 2005).

[15] See Indian Ministry of Power website: http://powermin.nic.in/JSP_SERVLETS/internal.jsp

As in the case of China, the IEA scenarios can be used to analyse the potential impact of accelerated cleaner coal technology deployment on power sector emissions in India. According to the World Energy Outlook (International Energy Agency, 2006b), the average efficiency of India's coal-fired plants in 2006 was 29% - a more conservative figure than those from Indian sources. Within both of the Outlook's scenarios, this average efficiency is expected to rise to 39% by 2030. The impact of a quicker introduction of cleaner coal technologies is illustrated in figure 3. If this pushed average efficiency to 45% by 2030, the reduction in CO_2 emissions in that year would be 184 million tonnes in the reference scenario or 140 million tonnes in the policy scenario. These reductions are much smaller than the equivalent reductions for China, but are still significant. Further reductions could be realised if carbon capture and storage technology were successfully commercialised. If 20% of new coal-fired plants in India were fitted with this technology between 2015 and 2030, an additional 61-102 million tonnes of CO_2 would be saved annually by 2030, depending on the scenario.

Figure 3: Impact of accelerated deployment of cleaner coal technologies on coal-fired power plant emissions in India (2030)



Source: Calculations based on figures used in (International Energy Agency, 2006b).

Implementing cleaner coal technologies in India

The main clean coal technologies with potential to contribute to mitigating carbon emissions in the short, medium and long term in India are examined below.

Short term

Over 90% of existing installed coal based power generation in India is currently subcritical and with a capacity below 250MWe per unit. There are also significant operational inefficiencies arising from a number of factors, including coal quality and supply problems, technical problems relating to plant operation and maintenance, managerial inefficiencies, a lack of information and awareness and the absence of incentives to improve performance (Ghosh, 2005). The latter arises largely as a result of the domination of government owned monopolies in the power sector – private ownership accounting for only 10% of total generating capacity with most of this focussed on gas-based generation (IEA, 2000). The poor quality of Indian coal is also a consistent barrier to improving generating efficiency. Much of the existing coal based energy plant and supply infrastructure in India is likely to be retired in the near future presenting significant opportunities for moving towards more efficient technologies (Ghosh, 2005). This would, however, require strategic thinking and planning on behalf of the Indian authorities.

The majority of 500MW plants are owned and operated by the National Thermal Power Corporation (NTPC) which has the technological know how and financial resources to build 800-1000MWe plants as well as supercritical plants (Massachusetts Institute of Technology, 2007). Whilst NTPC has the potential to roll out these more advanced technologies in the future, the greatest potential for reducing the environmental impacts of Indian coal fired power generation in the short term lies in improving the combustion efficiency of existing power plants. For a typical 500 MW coal based thermal power plant, there is a potential to reduce carbon dioxide emissions by about 40,000 tonnes per year due to improvements in thermal efficiency.

A limited number of Indian firms are engaged in the design and supply of boilers for thermal power plants. The two principal types of combustion technologies used in Indian boilers are pulverized fuel combustion (PFC) and circulating fluidised bed combustion (CFBC). Bharat Heavy Electricals Limited (BHEL), a public sector company, has been a pioneer in providing designs and supplying boilers since the 1960s. BHEL used to supply small capacity boilers with technical know-how from Czechoslovakia. It had a technology transfer agreement with Combustion Engineering (now part of Alstom) for about 30 years. BHEL current supply sub-critical units of up to 500 MW, without any technology transfer agreements. For super-critical units, they have recently entered into a collaboration agreement with Alstom.

Pulverised fuel boilers are a mature technology in India and the majority of the power plants use them. However, a number of significant gaps still exist affecting the overall efficiency and the performance of power plants. For example, the frequent variation in coal quality from mines directly affects the operating parameters and optimization of coal mills and control of excess air. Present boiler designs in India are generally based on volumetric heat loading and furnace area heat loading. These factors are fixed based on past experiences with similar coals, and lead to sub-optimal performance. There is a need to design boilers based on parameters such as properties of coal, combustion characteristics of the flame and the furnace, and radiative and convective heat transfer characteristics of heat transfer surfaces (e.g. water wall, superheaters and reheaters). Petrographic characteristics for coal must also be taken into account while designing boilers, to take care of slagging problems.

Coal burners in Indian power plants also currently result in significant emissions of NO_X. Norms for NO_X emissions are presently not enforced in the country. Though Indian manufacturers claim development of low NO_X burners, their performance is yet to be proved on a commercial scale. This highlights potential for cooperation with European firms that have a rich experience in low NO_X combustion systems (Department of Trade and Industry, 2000). There is also a know-how gap in India on economic low temperature heat recovery from flue gases below “dew point temperatures”, especially in extreme summer weather.

Combustion efficiency may also be improved with availability of on-line monitoring systems for pulverized coal distribution in tangential firing systems. Proven systems are not yet available in India. Availability of such systems would help in optimizing combustion air supply to the boiler and hence reduce energy losses. Beneficiation of coal is also relevant in the Indian context where there is a large percentage of ash in Indian coals. Beneficiated coal has yielded better control of combustion and the availability of the plant. Additional investments are required for this purpose. There is a need to develop low cost coal beneficiation technology to produce low ash and uniform quality of coal.

The thickness of ash deposits or fouling of tubes greatly affects the heat transfer efficiencies in boilers. Soot blowers are used for removal of scaling. The frequency of operation of soot blowers, however, is based on experiences rather than the thickness of ash deposits. A significant know-how gap exists here amongst companies involved in power generation in India. This is also a lack of capacity for R&D services related to measurements in the field on operating units, data analysis, and recommendations for improvements.

Circulating fluidized bed combustion (CFBC) boilers are being introduced in Indian thermal power plants by BHEL, Thermax Limited and Cethar Vessels Limited. CFBC offers a better option for using high ash content Indian coals with their frequently varying quality. There are a number of barriers for large-scale adoption of CFBC in India such as high wear of refractories in the cyclones, control of circulation of hot solids and also high overall costs.

Fluidization velocities in CFBC systems are in the range of 6 to 10 m/sec. For optimum combustion efficiencies, there is a need to optimize the fluidization velocities in CFBC boilers with respect to fuel properties and particle size. This is currently not being done by Indian boiler designers. The fluidization velocities are fixed based on experience. Investment requirements of CFBC boilers are higher than PF fired boilers. There exists a lot of scope for optimizing the costs of CFBC boilers.

Medium to long term

An important contribution to reducing carbon emissions from coal fired power generation in the medium term will be the introduction of supercritical pulverised coal plant. The construction of only supercritical pulverised coal power plants from now on would be able to reduce CO_2 emissions by one billion tons between 2005 and 2025 based on projected additions in capacity (Massachusetts Institute of Technology, 2007). NTPC is currently constructing the first supercritical pulverized coal power plant in India using technology supplied by a foreign equipment manufacturer. BHEL is attempting to compete here by entering into and agreement to license supercritical technology from a different international equipment manufacturer. There is the potential for such competition to reduce costs and make it more feasible for supercritical plants to be built in India in future.

In the medium to long term, gasification technology in India has the potential to make both incremental and radical reductions in carbon emissions from power plants and industrial processes such as fertiliser production. There is potential in India to for both IGCC and underground coal gasification (UCG). Both these technologies, however, represent medium to long term prospects.

UCG is an attractive technology for India due to the high ash content of much of India's coal reserves. Gasification of raw, unwashed coal via UCG can avoid the high financial and environmental costs of washing and transporting the coal. Two locations in India, one in Rajastan and another in Bengal-Bihar, have previously been identified as potential sites for UCG. To date no UCG initiatives have been undertaken, but there are several reports of potential initiatives.

In February 2005 GAIL (India) Ltd signed a memorandum of cooperation with Ergo Exergy Technologies Inc, Canada with the aim of cooperating on prospecting for coal and lignite deposits for UCG projects in India.[16] The intention is to follow this with joint design, construction, commissioning, operation and maintenance of pilot and commercial UCG plants in India. There is the potential for important knowledge transfer with Ergo contributing significant international expertise in UCG to assist GAIL in assessing the technical and economic viability of potential projects as well as production of UCG gas in commercial quantities with consistent enough quality to fuel combined cycle power plant. Ergo can also contribute know-how on UCG power generation and chemical synthesis for products such as methanol and clean diesel.

The most significant advance in gasification for power generation in India has been by BHEL, the largest power plant equipment manufacturer in India, which has built a small scale fluidised bed gasifier for testing purposes (6.2MW) using Indian coal. Some independent observers who have studied BHEL's gasifier have been quite positive about its potential viability and use in Integrated Gasification Combined Cycle (IGCC) plants. BHEL has also developed a Hot Gas Cleanup System (HGCS) using a granular bed filter system coupled to a 6 tonne per day (tpd) Pressurised Fluidised Bed Combustion (PFBC) system. Hot gas cleaning within the gasification process has, for many years, been one of the greatest challenges – particularly if the gas is to be burned in a modern gas turbine. Advanced gas turbines are very sensitive - impurities in the fuel gas mean that failures are more likely and more frequent maintenance is required.

BHEL have been talking to NTPC (National Thermal Power Corp) – the national utility – and the Indian Planning Commission about taking this work forward. Their ultimate aim is to build a 125MW IGCC demonstration at the Auraiya power plant (BHEL, 2006). NTPC, the Indian national power company, have also been thinking independently about gasification. Whilst, as noted above, NTPC are talking to BHEL about IGCC, it would appear that they are mainly focussing on the possibility of collaboration with US based organisations. In the past NTPC have received funding from USAID to carry out a feasibility study for a planned IGCC facility at its Dadri facility (BusinessLine, 2002). This includes testing of Indian coal in US labs such as the Gas Research Institute in Chicago.

More generally, the US is perceived to be working to persuade India to engage with it on gasification. This includes a bilateral US initiative to form a multi-funded energy programme that includes gasification in which India has invested US$10m, as well as a more multi-lateral approach via the Asia Pacific Partnership which the US is viewed to be coordinating. The US has

[16] See http://www.domain-b.com/companies/companies_g/gail/20050219_coal_gasification.htm

been fairly active in lobbying developing countries such as China and India to consider IGCC for many years, with little tangible success so far. This is generally perceived as an effort to recover some of the investment that the US government has invested in IGCC demonstration.

Long term

Carbon capture and storage (CCS) represents a long term potential consideration in India. At present there is limited interest for CCS in the country. At best it represents a long term prospect for reducing carbon emissions from coal. The most detailed report of current CCS activities in India is provided by Shackley (2007). He reports India's involvement in the Carbon Sequestration Leadership Forum (CSLF) as having provided the main impetus for India's interest in CCS. Shackley reports spin offs from the CSLF as including:

- An Indo-US meeting on CCS in Hyderabad in 2005
- A joint research programme on storage of CO_2 in basalts between the National Geophysical Research Institute (NGRI) in Hyderabad and Pacific North West Labs.
- Support of the US government Futuregen project to which India has contributed $10 million, although this only represents 1% of total anticipated costs

Other CCS relevant initiatives reported by Shackley include:

- Development of a project for CO_2-based Enhanced Oil Recovery (EOR) by the Oil and Natural Gas Corporation Ltd. (ONGC) for which it is hoping to earn CERs via the CDM
- An assessment of CCS by the National Thermal Power Corporation (NTPC) through its involvement in the CSLF. NTPC has also initiated some R&D on CO_2 capture from Indian coals.

Barriers to cleaner coal technologies in India

A number of barriers exist to the transfer of clean coal technologies to India. These are examined below in relation to each of the technologies mentioned above together with possible approaches to overcoming them.

There are number of risks attached to the introduction of newer technologies to improve combustion efficiency of thermal power plants. There are know-how gaps which exist for optimization of the performance of Indian thermal power plants. Internationally collaborative efforts in information sharing and R&D could benefit the industry in India. There are also cost related risks of investing in new combustion efficiency technologies. The estimated R&M (renovation and modernization) business of old power plants in India is Rs 50 billion (US$ 1,100 million). Uncertainty exists with regard to investments in R&M by old thermal power plants, as the present focus of R&M is more towards "restoration" of original capacity of plant (with high ash coal) and not for possible thermal efficiency improvements.

A number of interventions could help to promote adoption of new technologies for combustion efficiency improvements in India. Internationally collaborative projects, for example, could help bridge existing gaps in PFC and CFBC boiler technology. A shift in R&M focus to "cost effective technology upgrading" would help in improving plant output, availability and enhance the efficiency of power generation. This would require developing suitable and clear cut policy to address uncertainty related to the recovery of investments made in R&M. While the return on investments in R&M should be on par with "new builds", there is a need to devise a common "win-win" strategy for R&M activities between various stakeholders to put Indian plants on par with developed countries.

Power sector reforms also have a role to play. Independent Power Producers (IPPs) from developed countries, who are likely to bring with them new technologies, are not setting up plants in India. One important reason for this is the poor financial health of State Electricity Boards (SEBs) who are responsible for the distribution of electricity in different states in India. IPPs have to supply the power they produce via these SEBs but are faced with uncertainty as to whether SEBs will pay them for the power supplied. Although the Government of India modified the Electricity Act in 2003, the reforms in the states have not been fully implemented and many SEBs remain financially unsound.

The CDM may also have a role to play in facilitating the flow of improved combustion technologies to India. At present, however, no methodology for CDM projects in the power sector has been approved by the Executive Board of the CDM and project developers are unlikely to take the financial risk involved in getting the methodology approved. Action to develop new methodologies and present them to the Executive Board of the CDM for consideration is therefore important.

Apart from the general problem of high capital costs, a further cost consideration for IGCC in India arises from the high ash content of Indian coal. In order to take advantage of en-trained flow gasifiers, Indian coal must be combined with better quality imported coal or petroleum coke. Combing the coal with other feed stock is also necessary in order to produce a syngas of high enough quality to produce fertilizers. This implies that gasification for fertilizer production in India is a more expensive process than it might be for power generation. The higher cost might, however, be offset by higher margins on selling fertilizer relative to electricity.

Another technological risk exists in relation to the limited amount of testing of IGCC that has been done with Indian grade coal. All IGCC demonstration plants to date have been based on coals with different characteristics to Indian coal, especially ash content and ash fusion temperature. There is therefore limited existing empirical data on how these technologies would perform if applied to Indian coals. Some in Indian industry have expressed frustration with a lack of international information sharing on IGCC which hampers their ability to consider domestic applications of the technology (Ockwell, Watson et al., 2006). This implies a need for indigenous R&D and possibly full-scale demonstration before commercial plants would be viable. The work of BHEL on testing IGCC with Indian coal is therefore of vital importance here. This may be further assisted by engaging in collaborative, cross-industry, international initiatives to share information on advanced coal technologies, which would offer a means to reduce the risks and future costs associated with IGCC. One example of such an initiative is the US Electric Power Research Institute (EPRI)'s CoalFleet study. EPRI are open to non-US participants so it may be worthwhile for India to investigate the feasibility of engaging with this study.

One possible approach to overcoming the risks of high capital costs is for government to share the funding of demonstration activities with industry. This is the approach taken by the U.S.

Department of Energy for the Clean Coal Technology Program (known as the CCT program) where industry met 65% of the cost. The approach involved demonstration plants being set up at commercial scale by industry at their own privately owned premises and with industry retaining intellectual property rights. The Government's share in the cost of the project is then repaid by the industry only upon commercialisation of the technology (WEC 2005). It should, however, be noted that very little has in fact been paid back for advanced technologies such as IGCC due to a lack of commercialisation among the existing demonstration plants.

Participation in international initiatives to share information on technology, such as the UNFCCC’s TT:CLEAR, also has a clear role to play in encouraging technology transfer and developing India’s technological capacity in IGCC. India’s engagement with the Cleaner Fossil Fuels Taskforce of the Asia-Pacific Partnership on Clean Development and Climate represents another potential approach to information sharing that may yield useful opportunities for sharing and developing technological expertise. There may also be other opportunities such as participation in demonstration projects outside India – though careful thought should be given to the potential usefulness of these given the particular characteristics of Indian coal. Perhaps with this in mind, the Indian government decided in 2006 to contribute to the US government’s share of the costs of the FutureGen zero emissions coal project (see above).

Coordination of CCS activities in India has been designated the responsibility of the Department of Science and Technology (DST) through its role as the lead agency of the Government of India (GOI) in the CSLF. Shackley reports, however, that the level of coordination is currently low. Furthermore, at this early stage, opinion on CCS differs within as well as between the major players – Bharat Heavy Electricals Ltd. (BHEL), NTPC and ONGC.

With the main priority for the Government of India being, and likely to remain, economic development, Shackley (2007, p.1) concludes that:

> … it is not easy to imagine CCS – which increases overall generation capacity and demand for coal without increasing actual electricity supply – as being acceptable. Anything which increases costs even slightly is very unlikely to happen, unless it is fully paid for by the international community. The majority view point of the industry and GOI towards CCS appears to be that it is a frontier technology which needs to be developed further to bring down the cost through RD&D and deployment in the Annex-1 countries.

Future deployment of CCS in India is therefore likely to be reliant on its cost coming down to an acceptable level relative to the value of CERs under the CDM.

South Africa

Coal and the environment in South Africa

Like China and India, South Africa is significantly dependent on the use of coal – particularly in the power sector. This fuel produces around 60% of South Africa's primary energy (van der Riet, Gross et al., 2005). South Africa is the world's sixth largest coal producer and the one of the largest exporters. Production in 2005 was 247 million tonnes and consumption was 163 million tonnes (BP, 2006).

Electricity generation is dominated by coal-fired power plants. These plants generate approximately 92% of South Africa's power (Energy Research Centre, 2004). Since 1980, the policy has been to build very large plants of at least 3000MW in coalfield areas. All plants use standard pulverised fuel technology. For some plants, the use of dry cooling (due to lack of access to sufficient cooling water) means that thermal efficiency is comparatively low. Efficiency is a few percentage points lower than an equivalent plant with standard water cooling (ESI Africa, 2006).

Due to a lack of indigenous reserves and the need to work within trade sanctions under the apartheid regime, South African firms have played a leading role in the manufacture of gas and liquid fuels from coal. Companies such as Sasol have a long history in the development of liquefaction and gasification technologies to enable this (Energy Research Centre, 2004; Dyk, Keyser et al., 2006). Sasol was established in 1950 and completed its first coal gasification plant in 1955. Currently around 30 million tonnes of coal per year are gasified in 97 plants on two sites – Sasolburg and Secunda. The synthetic gas produced by these plants is processed further to produce chemicals and fuels. Around 40% of South Africa's liquid fuel requirements are met by the plants.

Much of South Africa's coal has a high ash content, low calorific value and low sulphur content. The sulphur content is moderate at 1.2% on average but the ash content can be up to 45% (Energy Information Administration, 2005). Most of South Africa's higher quality coal is exported to other markets. Particulate control from power plants is therefore seen as most important environmental priority for coal that is burned in domestic power plants (Winkler, Davidson et al., 2006). Electrostatic precipitators and high smokestacks have been installed at most plants.

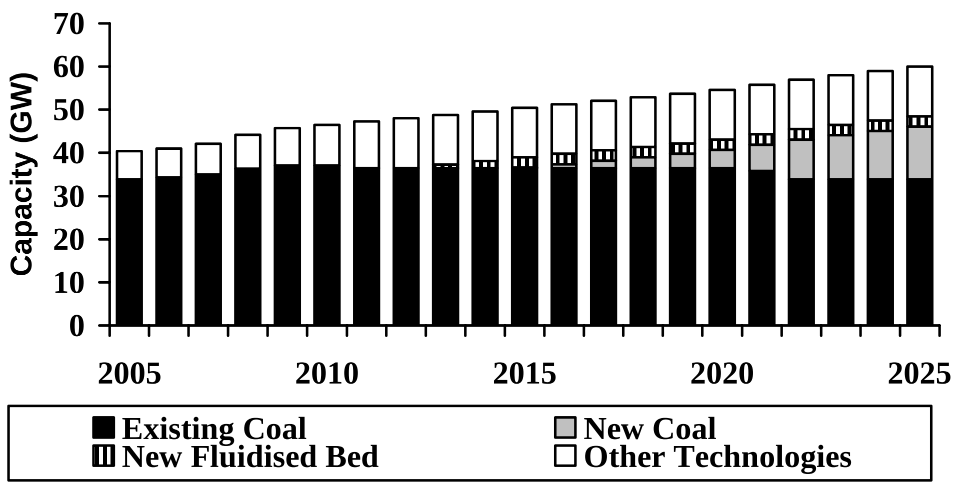
There has been much less emphasis on sulphur dioxide and NO_X control. No South African coal plants have flue gas desulphurisation (FGD) equipment fitted at present. Therefore, these plants account for the majority of annual SO_2 emissions in the country. There is a lack of recent official data that measures these and other emissions, despite the intention of the government to produce a State of the Environment report in 2005. The most recent figures available indicate that SO_2 emissions were 1.5 million tonnes in 2001 (Winkler, Davidson et al., 2006). This is a slight fall from the figure ten years earlier (1.8 million tonnes).

The majority of South Africa's CO_2 emissions from the use of fossil fuels stem from the combustion of coal[17]. Emissions have risen steadily each year as consumption of these fuels has increased. In the decade to 2003, CO_2 emissions from fossil fuel combustion rose from 316 million tonnes to 411 million tonnes. Within this, emissions from coal burning increased from 254 million tonnes (80% of the total) to 337 million tonnes (82% of the total).

South African energy projections and cleaner coal technologies

Whilst the IEA's World Energy Outlook gives detailed projections for coal-fired power plants in China and India, no details are given for South Africa. As a result, it is not possible to produce equivalent illustrative figures for potential CO_2 savings in South Africa. Instead, national projections can be used to explore these potential savings. In 2004, the National Energy Regulator of South Africa produced an updated integrated resource management plan. This provides a view of the evolution of the electricity system to 2025 (see Figure 4).

Figure 4. Future Projections of South African Power Plant Capacity



Source: (National Electricity Regulator, 2004; Winkler, Davidson et al., 2006)

These projections assume a 'business as usual' future for South African electricity over the next two decades. According to the data, electricity demand and coal-fired generation will increase steadily during this period. The majority of power will still be generated by standard coal units with efficiencies of around 32-33% in 2025. New plants will use this technology or (in a few cases), fluidised bed technology. More advanced technologies such as supercritical coal and IGCC are absent.

Taking these figures as a basis, and using the current average load factor of power plants in South Africa of 70% (Eskom, 2006), some illustrative figures for CO_2 emissions can be calculated. If the average efficiency of coal plants in 2025 is 32%, total annual emissions from

[17] Data from the Energy Information Administration, US Department of Energy. Reproduced at: http://www.cslforum.org/safrica.htm

coal-fired plants would be 282 million tonnes. Increasing average efficiency to 37% (the current OECD average) through investment in cleaner coal technologies would reduce emissions in 2025 to 244 million tonnes. A much more ambitious programme to increase average efficiency to 45% would reduce CO_2 emissions still further to 200 million tonnes. Note that this improvement would be harder to achieve than in India and China because of the use of energy-intensive dry cooling in South African plants. Furthermore, the total saving is smaller since the South African power system is smaller than that of India and China.

Cleaner coal technologies in South Africa

The main clean coal technologies with potential to contribute to mitigating carbon emissions in the short, medium and long term in South Africa are examined below.

Short Term
New coal-fired power plants are now being planned in South Africa for the first time in well over a decade. Economic growth has reduced the amount of spare capacity on the system. Eskom, the national electricity utility, is considering the use of cleaner coal technologies as part of this construction programme despite the absence of most options from the National Integrated Resource Plan. According to one senior Eskom manager, supercritical technology to increase thermal efficiency is being evaluated. However, there are no plans to use the most efficient supercritical equipment (ESI Africa, 2006). If dry cooling is necessary, this would only operate with an efficiency of 39% (the same as a new standard plant with wet cooling). This is higher than the efficiency of Eskom's existing plants (see above).

There are no fluidised bed plants in operation in South Africa at present. Eskom has been involved in some research into this technology using its own test equipment and in collaboration with universities. Several years ago, the company carried out a feasibility study together with two mining companies of the 'repowering' of an existing coal-fired power plant with a fluidised bed boiler (van der Riet and Begg, 2003; Energy Research Centre, 2004). This could burn coal that would otherwise be discarded as too difficult to combust in standard coal-fired plants. However, it would not reduce carbon emissions in comparison with such standard plants. In addition, Eskom has concluded that fluidised bed technology is still too expensive to be used instead of conventional boiler technology (van der Riet, 2007).

Medium Term
Although South Africa has a long-established track record in coal gasification technologies, there are currently no plans to deploy IGCC technology. The projections for future electricity supply from the National Electricity Regulator assume that this technology will not be used in the period to 2025 (Winkler, Davidson et al., 2006).

By contrast, there is considerable interest in developing Underground Coal Gasification technology in South Africa. In January 2007, gas flaring commenced at a pilot UGC plant at the Majuba coal-fired power station (Eskom, 2007). Instead of gasifying coal in a gasifier plant, UGC carries out the conversion process underground in coal seams that are difficult to mine. The gas is then extracted and burned or used as a chemical feedstock. The plan is to use this pilot plant to evaluate the feasibility of co-firing the 1200MW Majuba plant with gasified coal.

Long Term

Recently, investigations have started into the potential for carbon capture and storage technologies in South Africa (Engelbrecht, Golding et al., 2004). 85% of the large point sources of CO_2 that are thought to be suitable for carbon capture are owned by just two companies – Eskom (the national electricity utility) and Sasol (the synthetic fuels producer). In 2000, the CO_2 emissions from these two firms amounted to 218 million tonnes. This was over half the national emissions from fossil fuels.

Table 8 summarises some recent estimates of the size of South African storage reservoirs for CO_2 (Engelbrecht, Golding et al., 2004). As in many other areas of the world, saline aquifers offer the greatest potential for CO_2 storage. In South Africa, there are a number of potential drawbacks which mean that the full potential of these aquifers may not be exploited. The Katberg formation is remote and a long distance from point sources of CO_2 such as power stations. Other aquifers are thought to be unsuitable because they are not situated under a 'cap rock' that would prevent CO_2 leakage. Furthermore, the porosity of the rock in some aquifers could be relatively low which would limit the volume of CO_2 that could be stored.

Table 8. Potential Sinks in South Africa for Carbon Capture and Storage

Potential sink	Annual capacity (m tonnes)	Duration	Comments
Gas reservoirs	1	V long	Not an option now; enhanced recovery of natural gas is possible in future
Gold & coal mines	10	Varies	Uncertainty over integrity of storage sites; safety
CBM	Small	Long	Could recover methane for combustion, thereby reducing *net* CO_2 emissions.
Aquifers: • Vryheid formation • Katberg formation	18,375 (approx total) 1,600 (approx total)		Poor porosity and permeability may limit storage capacity; far from sources (Katberg); near to coal resources (Vryheid)

Source: (Engelbrecht, Golding et al., 2004)

For these and other reasons, the assessment that is summarised in the table divided the maximum storage potential of these aquifers by ten to give a conservative maximum storage volume. The assessment concluded that much more work was necessary to reduce the uncertainties and gain a more accurate picture of the CCS potential across all types of storage reservoir.

Barriers to cleaner coal technologies in South Africa

There are a number of barriers to the deployment of cleaner coal technologies in South Africa, many of which are similar to those in other countries. The pre-commercial status of some of the more advanced technologies in industrialised countries means that their deployment is unlikely for some time. However, even those cleaner coal technologies that have been available for some time such as flue gas desulphurisation, fluidised bed boilers and supercritical boilers have not yet been deployed in South Africa. This is despite the fact that two large and well established companies – Eskom and Sasol – account for a significant share of national coal demand.

One of the main reasons for this slow progress is economics. South Africa's electricity industry places a particular emphasis on low costs to supply aluminium smelters and other energy intensive industrial facilities (Venter, 2007). As a result, technologies with higher capital costs than traditional coal-fired power plant technology are viewed with some caution. This is even the case if these technologies can potentially reduce running costs due to efficiency improvements. According to Eskom, for example, fluidised bed boilers are attractive because they can burn 'discard' coal that would not otherwise be used – but they will not be deployed until the cost of the technology falls (van der Riet, 2007).

Despite this emphasis on costs, a number of other factors are likely to be important. One notable feature of the forecasts of future electricity industry development by Eskom and the government's Integrated Resource Plan is the absence of cleaner coal technologies as far ahead as 2025. Only fluidised bed boilers are seen as potentially viable within this timeframe. Supercritical coal-fired power plants, IGCC technology and carbon capture and storage are all excluded from these projections. This suggests a rather conservative view of the future. The absence of significant gasification technology deployment (e.g. as IGCC plants) is particularly surprising given the long history of Sasol in developing and using this technology. Furthermore, the recent tests of underground gasification technology by Eskom suggest a hope that this technology will contribute significantly in the medium term.

A further barrier to cleaner coal technology development and deployment is the lack of comprehensive environmental regulations. The emphasis is on controlling particulate emissions from coal fired plants and other facilities rather than other pollutants such as sulphur dioxide and CO_2. The absence of any flue gas desulphurisation plants in South Africa indicate that incentives for the control of local and regional pollutants are not yet strong enough – and, by implication, that it will be some time before incentives for CO_2 abatement are introduced.

The status of carbon capture and storage technology in South Africa is more in line with its status in China and India. The potential is recognised, but there is clearly much more work to do to develop the technology and to characterise potential CO_2 storage sites.

6. Conclusions and Ways Forward

This paper has examined the potential role of cleaner coal technologies in the mitigation of carbon emissions. It has focused on the barriers to the deployment of these technologies in developing countries – particularly China, India and South Africa. It has also examined some of the experience so far of transferring cleaner coal technologies to these countries.

Whilst some cleaner coal technologies are starting to make an impact in developing countries, the paper's analysis shows that the further development and deployment of these technologies could lead substantial reductions in carbon emissions over the next few decades. Coal is one of the world's most important energy sources. It is highly likely that this fuel will continue to account for a large proportion of primary energy needs, particularly in the countries analysed in this paper, for many years to come.

As this paper has illustrated, the term 'cleaner coal technology' encompasses a broad range of different technologies. These include incremental, near-term options such as efficiency improvements to existing coal-fired facilities. They also include 'end of pipe' technologies to reduce emissions of pollutants other than CO_2 such as sulphur dioxide and particulates. More advanced cleaner coal technologies to reduce CO_2 further such as carbon capture and storage are also included. Whilst it is important for governments and industry to focus on these more advanced technologies, their impact will be in the medium to long-term. In the meantime, there should also be significant emphasis on the diffusion of commercially available technologies which can make a serious impact more quickly.

Many such incremental improvements can pay for themselves through savings in operating costs – particularly the cost of fuel. Yet managerial, skills and financial barriers to implementation remain. More advanced technologies such as IGCC and carbon capture and storage offer further reductions in emissions. However, as the potential emissions reductions increase, so do costs, risks and other barriers to technology transfer and deployment. In the case of these more advanced technologies, technology transfer initiatives will be trying to combine two related processes – the transfer of technology from an industrialised country context to a developing country context *and* transfer from pre-commercial stages of technology development to commercial deployment.

The country case studies have revealed a number of further insights about the types of cleaner coal technology that could make a difference to CO_2 emissions in developing countries. These include the need to avoid an exclusive focus on the power sector. Whilst power sector emissions from coal burning are particularly important, there is scope for non-power sector improvements particularly in the large numbers of Chinese industrial firms that also rely on coal. There is also a need for a country specific focus in the development of some technologies. For example, gasification technology in India needs to account for the high ash content of indigenous coal.

Lessons for donor and recipient countries

Government-led approaches to cleaner coal technology transfer – particularly those that focus on more advanced technologies - have concentrated on both bilateral and multilateral mechanisms.

But the evidence suggests that these have had limited success so far. There is a need in future to build on policies that consider both ‘ends’ of the transfer process – i.e. actions by both donor and recipient countries. Crucially, the design of policies and actions needs to recognise that the main actors in implementing cleaner coal technology transfer and deployment are firms that are usually privately owned. These firms often have substantial pre-existing and successful experience of technology transfer on commercial terms. Indeed, cases of successful technology transfer identified in the case study countries have often involved firms acting independently of government initiatives. In most cases, these have not focused on the most advanced technologies.

For potential recipient countries of cleaner coal technologies, this paper suggests a number of specific actions. The case studies in the paper have demonstrated the value of country specific analysis of technology needs on different timescales – short, medium and longer-term. Such assessments can identify the scope for (and impact of) increasing the turnover of capital stock in coal-using sectors such as power stations and industrial boilers. There is also a need to assess the capacity of indigenous industries to absorb cleaner coal technologies and to identify areas of weakness.

The paper has provided clear evidence of numerous barriers to cleaner coal technology transfer and deployment that can be partly addressed by national policies in developing countries. One key area is environmental regulations which are often poorly enforced. This means that new coal-fired facilities are still being built that do not include readily available, proven emissions controls. Furthermore an opportunity is being missed to future-proof these facilities by insisting that they make it as easy as possible to retrofit CCS technology at some future date. Regulations governing intellectual property rights (IPR) could also help in some cases to build confidence amongst international firms and encourage them to engage in practices such as licensing and joint ventures. However, the available evidence suggests that the impact of IPR issues is variable and case specific.

For potential ‘donor’ countries and firms, the evidence suggests that there is a need for much more assistance to developing countries in the development, adaptation, financing and deployment of cleaner coal technologies. There is a need to learn more systematically from successful cases of private sector technology transfer which include, for example, the transfer of gasification technology to Chinese firms and the acquisition of supercritical technology by Chinese and Indian firms. It is also important for ‘donors’ of technology to pursue a broad approach to technology transfer that does not just focus on the installation of new technological hardware in developing countries. The transfer of the associated knowledge to help developing country firms to innovate independently is more challenging, but is also essential for genuine technology transfer to occur.

In the past, State-led technology transfer initiatives have sometimes failed to realise that donor governments and multilateral agencies do not have the power to transfer technologies themselves. Instead, they need to set a framework in which private sector actors are provided with appropriate incentives to reorient their normal commercial practices in a ‘cleaner’ or more ‘low carbon’ direction. In this context, further analysis and action is required about the way in which existing and often successful modes of transfer (e.g. joint ventures and licensing) may be adapted to benefit cleaner coal technologies.

Lessons for the UNFCCC and other multilateral frameworks

Whilst these ways forward can be pursued by single countries and bilaterally, there will be much scope for multilateral action, including via the UNFCCC, on several of them. However it is also important to consider action via a limited number of other (where possible pre-existing) institutional frameworks of a multilateral kind. Three areas for action are particularly important: financial mechanisms, mechanisms for technology development and international lending.

Developing new financial mechanisms that will assist in the specific problems of technology transfer and deployment has been a focus of multilateral discussions. As outlined in section 2 of this paper, the UNFCCC includes a mechanism for financing low carbon technologies in developing countries. In principle, the Clean Development Mechanism (CDM) could support cleaner coal technology transfer and deployment. So far, there has not been a significant focus on cleaner coal technologies – certainly not the more advanced technologies such as IGCC. For CCS projects, there are ongoing discussions about appropriate methodologies to determine how many certified emissions reductions (CERs) can be generated. Whilst many CDM projects include technology transfer in their design, it is too early to tell whether how much transfer will ultimately be realised in practice. Furthermore, it is unrealistic to expect that this mechanism will be enough on its own to realise the potential for cleaner coal technologies. Other mechanisms to scale up the amount of low carbon finance available from both public and private sources will be important. In this context, the World Bank's Clean Energy Investment Framework could have an important role to play.

Action in the area of intellectual property within multilateral frameworks could also be important. There is an ongoing debate about the extent to which developed countries could 'buy out' IPRs for low carbon technologies. In theory, this could help developing country firms to access these technologies. However, there is little evidence that this alone would aid the deployment of cleaner coal or other low carbon technologies. Access to relevant IPRs by developing country firms may be a necessary condition for successful acquisition in some cases, but is unlikely to be sufficient. This is because much of the knowledge required to develop, produce and deploy cleaner coal technologies is tacit and is not codified in patents.

One possible route to strengthen both codified and tacit knowledge in relevant technologies within developing countries might be to support joint R&D in technologies with more medium or long-term deployment prospects. Whilst there are some operational models for joint technology development between developed and developing countries, there is little evidence about their effectiveness in this regard. Further work is required to evaluate the usefulness of arrangements such as IEA implementing agreements on energy technologies or the task forces within the Asia Pacific Partnership to understand their strengths and weaknesses.

Finally, there is scope to develop new guidelines for international lending to developing countries by institutions such as the World Bank. Past experience has shown that these institutions can make a difference to the environmental performance of the projects they invest in, for example by specifying maximum sulphur emissions from power plants. In the same vein, a minimum regret strategy with respect to cleaner coal might be to insist that power plants supported by these institutions are ready for the addition of CCS technology as and when it becomes available.

References

Advanced Power Generation Technology Forum (2004). A Vision for Clean Fossil Power Generation. London, APGTF.

Banales-Lopez, S. and V. Norberg-Bohm (2002). 'Public policy for energy technology innovation: A historical analysis of fluidised bed combustion development in the USA.' *Energy Policy* 30: 1173-1180.

Bell, M. (1990). Continuing Industrialisation, Climate Change and International Technology Transfer. University of Sussex, SPRU.

Bell, M. (1997). 'Technology transfer to transition countries: are there lessons from the experience of the post-war industrializing countries?' in D. A. Dyker (ed) The technology of transition: Science and technology policies for transition countries. Budapest, Central European University Press.

BHEL (2006). IGCC Development Programme BHEL. 2006.

Bozeman, B. (2000). 'Technology transfer and public policy: a review of research and theory.' *Research Policy* 29: 627-655.

BP (2006). Statistical Review of World Energy. London, BP.

BusinessLine (2002). BHEL-Tiruchi looking to prove itself in new technology The Hindu Business Line. 2006.

Cheng, Y. (1998). Present Status and Development Opportunity of Coal Processing Technology in China. Presentation by the Clean Coal Engineering and Research Center to UK trade mission on clean coal technology, October.

Chhoa, T. (2006). Shell Clean Coal Energy in Asia Pacific. Gasification Technologies Conference 2006.

de Coninck, H. (2006). Technology transfer in the Clean Development Mechanism. Amsterdam, Energy research Centre of the Netherlands.

Department of Trade and Industry (2000). UK capability: Low NOx combustion systems, UK Department of Trade and Industry.

Department of Trade and Industry (2003a). Options for a low carbon future.DTI Economics Working Paper No. 4. London, DTI.

Department of Trade and Industry (2003b). Supercritical boilers for near term global markets Project Summary 270. London, DTI.

Department of Trade and Industry (2006). The Energy Challenge: Energy Review Report. London, The Stationery Office.

Dyk, J. C. v., M. J. Keyser, et al. (2006). 'Syngas production from South African coal sources using Sasol-Lurgi gasifiers.' *International Journal of Coal Geology* 65(3-4): 243-253.

EIA (2004). International Energy Outlook (IEO), Energy Information Administration (EIA).

Energy Information Administration (2005). South Africa Country Analysis Brief, US Department of Energy: http://www.eia.doe.gov/emeu/cabs/safrica.html.

Energy Information Administration (2006). International Energy Outlook 2006. Washington D.C., USA, US Department of Energy / EIA.

Energy Research Centre (2004). Energy for sustainable development: South African profile Phase I Final Report. Capetown, Energy Research Centre.

Engelbrecht, A., A. Golding, et al. (2004). The Potential for Sequestration of Carbon Dioxide in South Africa Report to the Dept of Minerals and Energy. Pretoria, CSIR.

ESI Africa (2006). 'Eskom's Generation Capacity Expansion Plans.' *ESI Africa* (2006, Issue 1).
Eskom (2006). Eskom Annual Report 2006. Johannesburg, Eskom.
Eskom (2007). 'Eskom's project revolutionises clean coal technology.' *Eskom Press Release.* 25th January
Evans, P. C. (1999a). Cleaner Coal Combustion in China: The Role of International Aid and Export Credit Agencies for Energy Development and Environmental Protection, 1998-1997, Centre for International Studies, MIT.
Evans, P. C. (1999b). 'Japan's Green Aid Plan: The Limits of State-Led Technology Transfer.' *Asian Survey* 39(6): 825-844.
Ghosh, D. (2005). Assessment of Advanced Coal-Based Electricity Generation Technology Options for India: Potential Learning from U.S. Experiences. BCSIA Discussion Paper 2005-02, Energy Technology Innovation Project, Kennedy School of Government, Harvard University.
Grubler, A. and N. Nakicenovic (1991). 'Long Waves, Technology Diffusion and Substitution.' *Review* 14: 313-342.
Haites, E., M. Duan, et al. (2006). Technology Transfer by CDM Projects. Toronto, Canada, Margaree Consultants Inc.
Heaton, G. R., R. D. Banks, et al. (1994). Missing Links: Technology and Environmental Improvement in the Industrializing World. Washington DC., World Resources Institute.
Holt, N. (2003). 'Operating experience and improvement opportunities for coal-based IGCC plant.' *Materials at High Temperatures* 20(1).
House of Commons Select Committee on Energy (1981). The Government's Statement on the New Nuclear Power Programme. London, HMSO.
ICTSD and UNCTAD (2003). Intellectual Property Rights: Implications for Development, International Centre for Trade and Sustainable Development and UNCTAD.
IEA (2000). Coal in the Energy Supply of India. Paris, International Energy Agency (IEA).
IEA Greenhouse Gas R&D Programme (2001). Putting Carbon Back into the Ground, IEA Greenhouse Gas R&D Programme.
Intergovernmental Panel on Climate Change (2005). IPCC Special Report: Carbon Dioxide Capture and Storage, IPCC.
Intergovernmental Panel on Climate Change (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the IPCC. Geneva, Switzerland, IPCC.
International Energy Agency (2006a). China's Power Sector Reforms: Where to Next? Paris, OECD/IEA.
International Energy Agency (2006b). World Energy Outlook 2006. Paris, OECD/IEA.
IPCC (2000). Methodological and technological issues in technology transfer. Cambridge, Cambridge University Press.
Ivarsson, I. and C. G. Alvstam (2005). 'Technology transfer from TNCs to local suppliers in developing countries: A study of AB Volvo's truck and bus plants in Brazil, China, India, and Mexico.' *World Development* 33(8): 1325-1344.
Jaeger, H. (2006). 'Japan 250 MW Coal Based IGCC Demo Plant Set for 2007 Start-Up.' *Gas Turbine World* May-June.
Jin, Y. and X. Liu (1998). The Preliminary Research on China's Clean Coal Technology Acquisition Preliminary report for CCICED Working Group on Trade and Environment. Beijing, Guanghua School of Management.

Joskow, P. and N. Rose (1983). 'The Effects of Technological Change, Experience, and Environmental Regulation on the Construction Cost of Coal-Burning Generating Units.' *RAND Journal of Economics* 16: 20.

Kjaer, S., J. Bugge, et al. (2004). 'Europeans still aiming for 700 degC steam.' *Modern Power Systems*. November.

Martinot, E., J. E. Sinton, et al. (1997). 'International technology transfer for climate change mitigation and the cases of Russia and China.' *Annual Review of Energy and the Environment* 22: 357-401.

Maskus, K. (2000). Intellectual Property Rights in the Global Economy Institute for International Economics, Global Economy Institute for International Economics.

Massachusetts Institute of Technology (2007). The Future of Coal: Options for a Carbon Constrained World. Boston, MA, USA, MIT.

McGregor, R. (2007). 'China's Power Capacity Soars.' *Financial Times.* 6th February

McMullan, J., B. Williams, et al. (2001). 'Strategic considerations for clean coal R&D.' *Energy Policy* 29: 441-452.

Ministry of Power (2007). Performance Report 2006. New Delhi, India.

Modern Power Systems (1998). 'Advanced Technology for Nordjyllandsværket.' *Modern Power Systems*. May.

National Electricity Regulator (2004). National Integrated Resource Plan 2 (NIRP2) 2003/4. Pretoria, National Electricity Regulator.

National People's Congress (2006). The Eleventh Five-Year Plan for National Economic and Social Development. Beijing, National People's Congress.

Neff, S. (2005). Review of the Energy Policy Act 2005, Columbia University.

Nelson, R. R. and H. Pack (1999). 'The Asian miracle and modern growth theory.' *Economic Journal* 109(457): 416-436.

Ockwell, D. and J. C. Lovett (2005). 'Fire assisted pastoralism vs. sustainable forestry - The implications of missing markets for carbon in determining optimal land use in the wet-dry tropics of Australia.' *Journal of Environmental Management* 75(1): 1-9.

Ockwell, D., J. Watson, et al. (2006). UK–India collaboration to identify the barriers to the transfer of low carbon energy technology.Report by SPRU, IDS and TERI to Defra. London, Defra.

Parliamentary Office of Science and Technology (2005). Carbon Capture and Storage (CCS) 238. London, POST.

Planning Commission (2006). Report of the Expert Committee on Integrated Energy Policy New Delhi, Planning Commission, Government of India.

Platts (2005). 'Bush budget holds coal program harmless.' *Emissions Daily*. 15th February.

Robinson, R. D. (1991). The International Communication of Technology: A Book of Readings. New York, Taylor and Francis.

Saad, M. and G. Zawdie (2005). 'From technology transfer to the emergence of a triple helix culture: The experience of Algeria in innovation and technological capability development.' *Technology Analysis & Strategic Management* 17(1): 89-103.

Schnepp, O., M. A. von Glinow, et al. (1990). United States - China Technology Transfer. New Jersey, Prentice Hall.

Shackley, S. (2007). Prioritised Assessment of CO2 Capture and Storage (CCS) Public, Policy and Regulatory Issues in India Unpublished draft, Tyndall Centre.

Shackley, S., C. McLachlan, et al. (2004). The Public Perceptions of Carbon Capture and Storage Tyndall Centre Working Paper No.44. Norwich, Tyndall Centre.
Sivaramakrishnan, R. and T. A. Siddiqi (1997). 'Growth of electricity use in India, and strategies for reducing greenhouse gas emissions.' *International Journal of Global Energy Issues* 9(4-6): 225-236.
Sustainable Development Commission (2006). The Role of Nuclear Power in a Low Carbon Economy. London, Sustainable Development Commission.
Tampa Electric Company (2002). Tampa Electric Polk Power Station Integrated Gasification Combined Cycle Project Final Technical Report to the US Department of Energy.
TERI (1998). Energy Data Directory & Year Book, 1997/98. Delhi, TERI.
TERI (2006). Climate Change and Technology Transfer: Status Review Paper Report to British High Commission. New Delhi, TERI.
TERI (2007). Exploring opportunities for technology transfer to developing countries for climate change mitigation. Delhi, TERI.
UK Commission on Intellectual Property Rights (2002). Integrating Intellectual Property Rights and Development Policy. London, Commission on Intellectual Property Rights.
US Department of Energy (1999). Market-based advanced coal power systems: Final report, US DoE.
US Department of Energy (2003). Clean Coal Technology Programs: Program Update 2003, Volume 1, US DoE.
US Department of Energy (2004). FutureGen: Integrated electric Power production and carbon sequestration research initiative, US DoE Office of Fossil Energy.
van der Riet, M. (2007). Clean Coal Technologies for Power Generation - A South African Perspective. IEA NEET Workshop on Energy Technology Collaboration, Johannesburg, South Africa, 20th February.
van der Riet, M. and J. H. Begg (2003). 'Clean coal technologies for South Africa.' *ESI Africa* (Issue 2, 2003).
van der Riet, M., C. Gross, et al. (2005). 'Eskom's Coal Research Programme.' *ESI Africa* (Issue 4, 2005).
van Schalkwyk, M. (2006). Chair's Summary. Ministerial Indaba on Climate Action. Kapama Lodge, South Africa.
van Zuylen, H. J. and Y. S. Chen (2003). 'Technology transfer of intelligent transport systems - China and the Netherlands.' in(ed) Transportation Management and Public Policy 2003: 94-100.
Venter, I. (2007). 'Clean Coal: The world is going all out for the ultimate – zero-degree emission.' *Mining Weekly*. 9th February.
Wang, K., C. Wang, et al. (2007). 'Scenario analysis on CO2 emissions reduction potential in China's iron and steel industry.' *Energy Policy* 35(4): 2320-2335.
Watson, J. (1997). Constructing success in the electric power industry: Combined cycle gas turbines and fluidised beds.SPRU. Brighton, University of Sussex.
Watson, J. (2005). Advanced Cleaner Coal Technologies for Power Generation: Can they deliver? BIEE/UKERC Academic Conference, Oxford, 22-23 September.
Watson, J. (2006). UK Policy for Carbon Capture and Sequestration: Strategies for Innovation and Deployment. 26th Annual North American Conference of the USAEE/IAEE, Ann Arbor, MI, USA, 24-27 September.

Watson, J. and X. Liu (2002). 'Cleaner Coal Technology Transfer: Obstacles, Opportunities and Strategies for China.' in D. Runnalls, R. Ye, K. v. Moltke and W. Yang (ed) Trade and Sustainability: Challenges and Opportunities for China as a WTO Member. Winnipeg, IISD.

Watson, J., G. Oldham, et al. (2000). The Transfer of Cleaner Coal Technologies to China: A UK Perspective Report to the DTI, No. COAL R196. London, DTI.

Winkler, H., O. Davidson, et al. (2006). Energy policies for sustainable development in South Africa: Options for the future. Cape Town, South Africa, Energy Research Centre, University of Cape Town.

World-Bank (2006). Clean Energy and Development: Towards an Investment Framework, World Bank.

Worrell, E., R. van Berkel, et al. (2001). 'Technology transfer of energy efficient technologies in industry: a review of trends and policy issues.' *Energy Policy* 29(1): 29-43.

Yamin, F. (2003). Intellectual property rights, biotechnology and food security.IDS Working Paper No. 203; Biotechnology Policy Series No.22. Brighton, UK, IDS.

Yu, Z. (1999). Promoting Clean Energy and Developing Clean Coal Technology. Proceedings of the Second International Symposium on Cleaner Coal Technology, Beijing, November.

Yu, Z., Y. Xiao, et al. (2004). Policy study on development and utilization of CCT.China National Energy Strategy and Policy 2020, Clean Coal Engineering & Research Center of Coal Industry and Institute of Engineering Thermophysics of Chinese Academy of Sciences.

Zhang, A. and X. Zhao (2006). Efficiency Improvement and Energy Conservation in China's Power Industry Background Report for the Stern Review.