COAL INDUSTRY ADVISORY BOARD CIAB

INTERNATIONAL ENERGY AGENCY

# Clean Coal Technologies

## Accelerating Commercial and Policy Drivers for Deployment

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Coal is and will remain the world's most abundant and widely distributed fossil fuel. Burning coal, however, can pollute and it produces carbon dioxide. Clean coal technologies address this problem. The widespread deployment of pollution-control equipment to reduce sulphur dioxide, $NO_x$ and dust emissions from industry is just one example which has brought cleaner air to many countries. Since the 1970s, various policy and regulatory measures have created a growing commercial market for these clean coal technologies, with the result that costs have fallen and performance has improved. More recently, the need to tackle rising $CO_2$ emissions to address climate change means that clean coal technologies now extend to include those for $CO_2$ capture and storage (CCS).

This short report from the IEA Coal Industry Advisory Board (CIAB) presents industry's considered recommendations on how to accelerate the development and deployment of this important group of new technologies and to grasp their very significant potential to reduce emissions from coal use. It identifies an urgent need to make progress with demonstration projects and prove the potential of CCS through government-industry partnerships. Its commercialisation depends upon a clear legal and regulatory framework, public acceptance and market-based financial incentives. For the latter, the CIAB favours cap-and-trade systems, price supports and mandatory feed-in tariffs, as well as inclusion of CCS in the Kyoto Protocol's Clean Development Mechanism to create demand in developing economies where coal use is growing most rapidly.

This report offers a unique insight into the thinking of an industry that recognises both the threats and growing opportunities for coal in a carbon-constrained world.

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## INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) is an autonomous body which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

It carries out a comprehensive programme of energy co-operation among twenty-seven of the OECD thirty member countries. The basic aims of the IEA are:

- To maintain and improve systems for coping with oil supply disruptions.
- To promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations.
- To operate a permanent information system on the international oil market.
- To improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use.
- To promote international collaboration on energy technology.
- To assist in the integration of environmental and energy policies.

The IEA member countries are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Republic of Korea, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. Poland is expected to become a member in 2008. The European Commission also participates in the work of the IEA.

## ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of thirty democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Republic of Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.
The European Commission takes part in the work of the OECD.



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## COAL INDUSTRY ADVISORY BOARD

The Coal Industry Advisory Board (CIAB) is a group of high-level executives from coal-related industrial enterprises, established by the International Energy Agency (IEA) in July 1979 to provide advice to the IEA on a wide range of issues relating to coal. The CIAB currently has 45 members from 19 countries, contributing valuable experience in the fields of coal production, electricity generation and other aspects of coal use, trading and transportation.

# FOREWORD BY THE EXECUTIVE DIRECTOR OF THE IEA

Coal is an important source of primary energy for the world and demand is growing rapidly in many developing countries as they enjoy a period of long-overdue economic growth. Over the 50 years from 2000 to 2050, demand might double to exceed 7 000 million tonnes of coal equivalent and so account for 28% of the world's primary energy supply, up from today's 25%. Strong environmental policies could see substantially lower coal use – it is, after all, the most carbon-intensive fuel. However, given coal's abundance, there will be pressure to exploit this resource for energy security and economic reasons. Improving coal's environmental performance is key to coal's future role in the energy mix. In particular, a group of technologies, known as carbon dioxide capture and storage (CCS), offers the potential to balance the sometimes competing goals of energy security, economic development and environmental sustainability.

In recent IEA work, we found that $CO_2$ emissions could be reduced by 32 $GtCO_2$ below a baseline scenario by 2050 with the accelerated deployment of a number of low-carbon technologies and efficiency measures (IEA, 2006a). CCS accounts for 20% of this reduction, half of which is CCS at coal-fired power plants. CCS is an important component of any climate change mitigation strategy.

I welcome the coal industry's involvement in a growing number of projects, partnerships and programmes aimed at developing and demonstrating CCS at a scale relevant to commercial operation. Proving the capture technologies at scale is an important step, but there are others. We know that more experience and confidence is needed in $CO_2$ storage. It must grow to an industry of equivalent size to today's natural gas industry by 2050 if CCS is to have the impact that our analysis projects. There needs to be an attractive return for those prepared to invest in what is presently a costly technology. This report presents industry's thinking on the types of incentives that could encourage the commercial deployment of CCS. I am pleased to see the IEA Coal Industry Advisory Board taking this initiative and would urge policy makers to examine carefully the many recommendations and respond by creating opportunities for early demonstration.

Finally, I wish to reflect on the role of conventional clean coal technologies. These are not as widely deployed as they should be. The political support needed for CCS to succeed will only be forthcoming if all aspects of coal's environmental footprint are seen to be improving. In this respect, developed countries have much to offer developing nations – technologies and the experience of applying these within policy frameworks that deliver results. Industry itself has an important role in ensuring the spread of best practices.

I am pleased to publish this report, under my authority as Executive Director, as part of the IEA role to advise G8 leaders on alternative energy scenarios and strategies aimed at a clean, clever and competitive energy future. The views and recommendations expressed do not necessarily reflect the views or policies of the IEA or of the IEA member countries.

**Nobuo Tanaka**
Executive Director

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# EXECUTIVE SUMMARY AND POLICY RECOMMENDATIONS

The momentum driving coal consumption growth in the developed and developing world needs to be reconciled with a growing commitment by many countries, including IEA member countries, to significantly reduce greenhouse gas (GHG) emissions in order to mitigate global climate change. Continued prosperity in the developed world is currently linked to the maintenance and, in some cases, the expansion of coal-based electricity generation. Elsewhere, economic growth in the past two decades has, according to the World Bank, enabled the greatest reduction in poverty in history, primarily in developing Asian countries. However, recently issued reports, including *The Stern Review: The Economics of Climate Change* and the latest reports of the Intergovernmental Panel on Climate Change (IPCC), have emphasised that atmospheric $CO_2$ concentrations should not exceed the range of 450-550 ppm by 2050, in order to avoid catastrophic economic consequences associated with an average global temperature rise greater than 2°C. They also stressed the need to begin reducing total global emissions within ten to fifteen years, and to achieve absolute cuts in emissions from developed countries of 60-80% by 2050. While not universally accepted, the reports have informed a growing scientific and political consensus to seek real reductions in total global GHG emissions in the next three to four decades.

Forecasts by reputable international and national entities project moderate coal demand growth in the developed world, accompanied by strong coal demand growth in the developing world. Recently released statistics confirm that coal is the fastest growing component of global energy supply; the widespread distribution and competitive cost of coal ensures that its role in meeting energy demand will remain large in the future. Indeed, many major developing countries intend to rely on coal to fuel continued economic growth. While there are alternative sources of energy, geographic concentration, expense or long lead times make it unlikely that they will displace coal in electricity generation to any significant extent in the foreseeable future. Therefore, it is highly unlikely that the dramatic GHG emission reductions by 2050, as called for in *The Stern Review* and IPCC assessments, will be met without coal playing a major role through new, low-emission technologies.

Clean coal technologies (CCTs) have been developed and deployed to reduce the environmental impact of coal utilisation over the past 30 to 40 years. Initially, the focus was upon reducing emissions of particulates, $SO_2$, $NO_X$ and mercury. The coal sector – producers, consumers and equipment suppliers – as well as governments and agencies in countries where coal is essential, have a long experience of stimulating clean coal technology deployment. Experience continues to grow as the technologies are introduced and spread in developing countries. The clean coal technology focus in IEA countries has moved to the development and operation of low and near-zero GHG emission technologies like carbon dioxide capture and storage (CCS). Deployment of CCS, as part of an effort to reduce GHG emissions, has been endorsed by G8 leaders, the IEA, *The Stern Review* and the IPCC. The IEA has identified four groups of CCTs (coal upgrading, efficiency improvements at existing power plants, advanced technologies and near-zero emission technologies) which can dramatically reduce GHG emissions. The CIAB believes that $CO_2$ transport and storage must also be developed as a fifth group of CCTs needed to reduce GHG emissions.

To achieve the ambitious GHG emission reduction targets proposed by the IPCC and others, and to maintain economic progress, it is necessary to decarbonise large parts of the electricity generation sector in developed and developing countries; this will demand the widespread deployment of CCS. Review of past efforts to stimulate innovation, development and deployment suggests that intra-national relationships (academia-business-government), national support and international co-ordination and support will be essential elements of CCS deployment.

The CIAB believes that the drivers to develop and deploy emission-reducing technologies and mechanisms to support deployment of low-GHG emission technologies can evolve to create the conditions necessary to stimulate more rapid research, development and deployment of CCS. It has identified several essential policy and commercial drivers that have been used to create and promote deployment of cleaner technologies while maintaining the efficiency and commercial viability of fossil-fuelled energy systems. The CIAB believes that these drivers, tailored to stimulate development and deployment of low-carbon technologies, can reduce the time frame for achieving significant GHG emission reductions and recommends that they should be strongly supported, endorsed and accelerated by national and international policy makers. These drivers include:

- Establishing a clear, balanced legal framework for $CO_2$ transport and storage;
- Promoting public understanding and acceptance of $CO_2$ capture and storage (CCS);
- Funding CCS research, development, and deployment;
- Establishing tax incentives and loan guarantees for CCS R,D&D and commercial projects;
- Supporting commercial opportunities for use of $CO_2$ for enhanced oil recovery (EOR) and enhanced coalbed methane production as a means of developing CCS technology and infrastructure;
- Promoting commercial opportunities in transport fuel and chemical production from coal as a means of developing CCS technology and infrastructure;
- Supporting market-based responses, such as GHG cap-and-trade systems, to speed the ultimate commercialisation of CCS;
- Encouraging mandatory price supports and feed-in tariffs based on the avoided emissions from systems with CCS; and,
- Promoting participation of emerging economies in CCS development and deployment.

As a recognised authority on energy supply, demand and security, the IEA has a unique potential to stimulate the process of deploying CCS by endorsing the use of these drivers and providing advice on their implementation to policy makers in member countries. A specific action would be to advise that CCS be included in the Kyoto Protocol's Clean Development Mechanism to create demand for this technology in developing economies where coal use is growing most rapidly. Furthermore, through its energy technology implementing agreements and co-operative agreements with non-member countries, the IEA can raise the profile of all the above recommendations on policy and commercial drivers and significantly improve the rate at which CCS is developed and deployed in the world.

# INTRODUCTION

For this report, the IEA Coal Industry Advisory Board (CIAB) has assessed commercial and policy drivers that have been employed to encourage development and deployment of clean coal technologies (CCTs) and other low-emission technologies in International Energy Agency (IEA) member countries and non-member countries.

The report briefly reviews the need for coal and the range of available CCTs. Following this, the commercial and policy drivers that could accelerate CCT development and deployment are discussed. The discussion is based on initial contributions from CIAB Members which were subsequently considered at their Plenary meeting on 7th November 2007 and at a workshop *"$CO_2$ Capture and Storage - international progress and future prospects"*, co-hosted by the CIAB, the Royal Society and the Royal Academy of Engineering immediately after the Plenary. $CO_2$ capture and storage (CCS) is at the forefront of technologies to reduce $CO_2$ emissions and a summary of the policy discussions at these two meetings forms part of this report. Finally, each of the recommended commercial and policy drivers is individually reviewed.

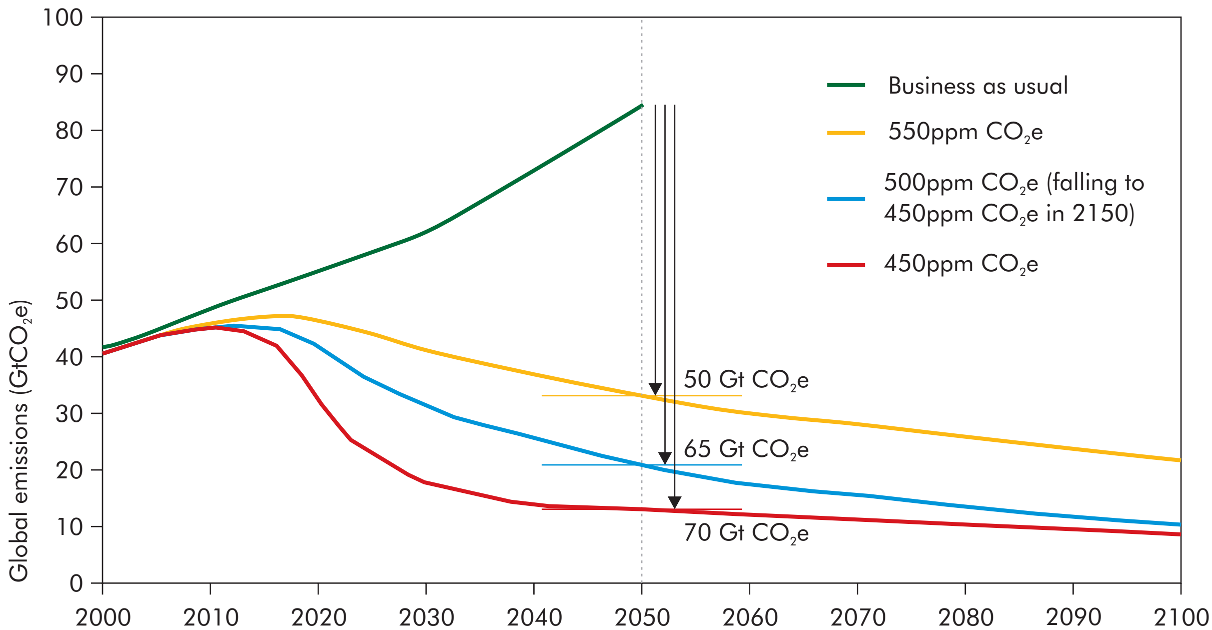
The CIAB believes that there is a high likelihood that world coal demand will continue to grow strongly over the coming decades. This belief is supported by IEA forecasts and is widely shared by many member countries, non-member countries and energy industry experts. Even if coal's proportion in the energy mix were to decline with stronger environmental policies, absolute coal demand would grow because of the forecast increase in global energy demand by 2030. Developed countries have long depended upon coal, and strong economic growth in the developing world is primarily fuelled by coal, not only for electricity generation but also for the production of heavy industrial goods such as steel and cement.

The *BP Statistical Review of World Energy* (BP, 2007) underscores the continuing trend of coal demand growth. While global gas and oil consumption increased 2.5% and 0.7% respectively in 2006, coal consumption grew by 4.5% – nearly double the total primary energy growth rate of 2.4%. Based upon the BP data, global coal consumption increased by more than 1.4 billion physical tonnes between 2001 and 2006. About 90% of this growth was in the Asia-Pacific area – driven primarily by China and India, but also by Chinese Taipei, South Korea, Japan, Malaysia and Thailand.

The momentum driving coal consumption growth in the developed and developing world needs to be reconciled with a growing commitment by many countries, including IEA member countries, to significantly reduce greenhouse gas (GHG) emissions in order to mitigate global climate change. Recent findings by national and international bodies have added urgency to that commitment. For example, in October 2006, this urgency was a key point made in the presentation by Sir Nicholas Stern of *The Economics of Climate Change*, a report prepared on behalf of HM Treasury, the UK government's finance department (Stern, 2007). Although his conclusions are not universally accepted, Stern argues that the economic implications of permitting global warming increases beyond 2°C are potentially catastrophic and, as a consequence, the atmospheric concentration of $CO_2e$ needs to be kept below 550 parts per million (ppm). Using the

Intergovernmental Panel on Climate Change (IPCC) climate models, he concluded that to keep global $CO_2e$ concentrations in a range of 450-550 ppm by 2050, total global $CO_2e$ emissions must begin to decline within the next ten to fifteen years (Figure 1). Stern's analysis further concluded that developed countries must make absolute cuts in emissions of 60-80% by 2050. Stern notes that, *"the power sector around the world would need to be at least 60% decarbonised by 2050 for atmospheric concentrations to stabilise at or below 550 ppm $CO_2e$ …"* (*ibid.*, p. xvii). In the first half of 2007, scientific updates on global climate change issued by the IPCC also informed on economic and policy issues, and stressed the need to reduce total global emissions within ten to fifteen years in order to keep global temperature increases to a maximum of 2°C (IPCC, 2007).

**Figure 1. Business-as-usual emissions and stabilisation trajectories for 450-550 ppm atmospheric concentration of $CO_2e$ showing "mitigation gaps" for 2050**




Source: Stern, 2007.

These reports are having a significant impact on policy thinking, particularly in Europe. The European Council and the European Parliament have called for action to limit global temperature increase to 2°C and have endorsed measures for binding emission reductions with deadlines. Germany's Chancellor Merkel, who until June 2007 was President of the European Council and chair of the G8, emphasised the need for a commitment from EU members and G8 leaders to a maximum global temperature increase of 2°C and a minimum 50% reduction in GHG emissions by 2050. At the June 2007 G8 Summit in Heiligendamm, Germany, the USA and major developing countries like China and India, were successfully brought into a UN-led effort to craft a replacement for the Kyoto Protocol, which expires in 2012.

Clearly, there is a growing scientific and political consensus to seek real reductions in total global GHG emissions in the next three to four decades, rather than delaying further. The reconciliation of the drive to consume coal for economic activity and the commitment to reduce GHG emissions in this time frame requires that an enormous technological effort be made in the next two decades. There is a significant number of available low-emission technologies which hold considerable promise for reducing GHG emission growth, including nuclear power and renewable energy; but, even in combination, these will not be able to replace the widespread use of fossil fuels. Coal remains the fossil fuel of choice for electrical power generation and certain industrial applications in many developed and developing economies because of its supply security and competitive cost. Consequently, there is a need to accelerate the development and deployment of technologies that will reduce the emissions from the use of coal, as well as from the use of natural gas and oil. A study released by the Massachusetts Institute of Technology concluded, *"… that $CO_2$ capture and sequestration (CCS) is the critical enabling technology that would reduce $CO_2$ emissions significantly while also allowing coal to meet the world's pressing energy needs."* (MIT, 2007, p. x).

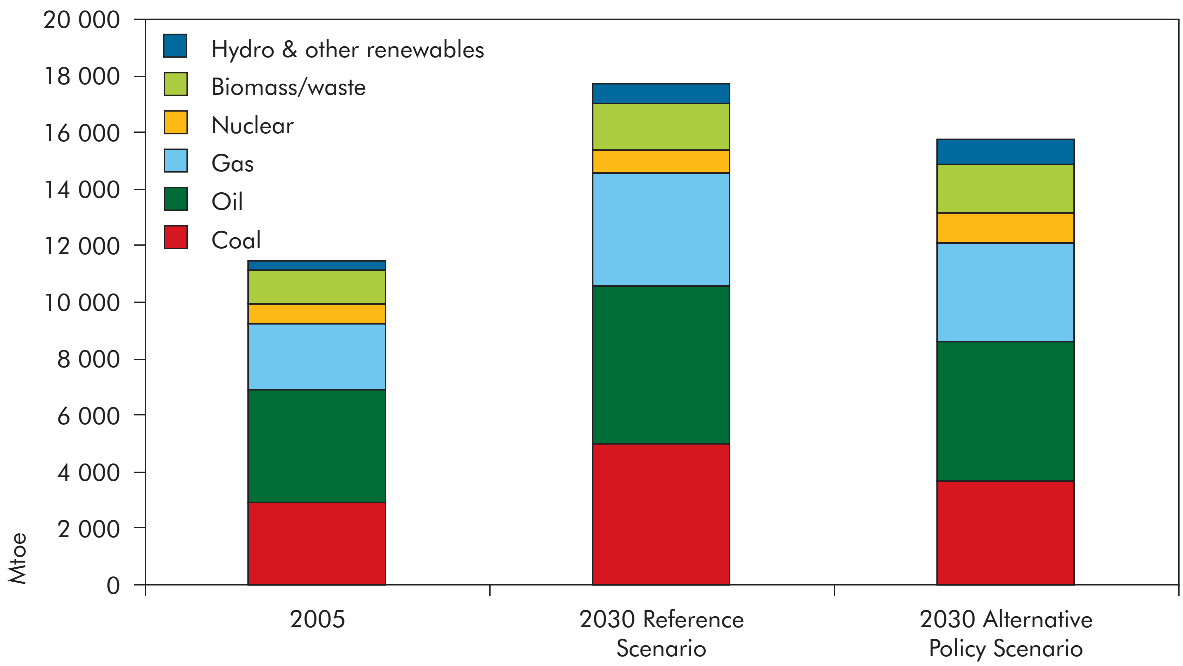
The magnitude of the task of accelerating development and deployment is enormous. The world's major energy systems entail planning time frames of ten to twenty years and asset lives of forty to sixty years. Bringing forward the development and deployment of new low-emission technologies poses an exceedingly complex and difficult challenge to government, business and society.

Moreover, as *The Stern Review* and other studies emphasise, the deployment of low- or "near-zero" emission technologies must occur not only in the industrialised world, but also in the developing world. In the discussions leading up to the 2007 G8 Summit in Germany, it was India that noted that industrialised countries would need to furnish technologies to reduce $CO_2$ emissions that are affordable within the context of developing economies. The developed countries need to take the lead in providing the technologies and the legal/regulatory implementation frameworks for deploying and refining them – first in their own economies, but quickly followed by stimulating and facilitating widespread adoption in developing economies.

# THE NEED FOR COAL

As the IEA has noted in recent statements, only a portfolio of cleaner fossil fuels together with energy efficiency measures, nuclear and renewable energy can provide the price stability, supply security and widespread availability needed over the next few decades for the developed world to maintain its prosperity and for the developing world to fuel its economic growth and alleviate poverty (IEA, 2007a and IEA, 2007b). Moreover, the push for development to alleviate poverty continues to place priority on economic growth and the concomitant urbanisation and mass infrastructure development that characterises rapidly growing Asian economies. The need for new ports, roads, railways, airports and housing drives increased demand for electricity, steel and cement which are traditionally reliant on coal to fuel their production.

**Figure 2. Energy demand changes under two scenarios for 2030**




Source: IEA, 2007c.

According to the IEA *World Energy Outlook 2007 (WEO 2007)* Reference Scenario, global primary energy demand is projected to increase by 55.1% between 2005 and 2030, to a total of 17 721 million tonnes of oil equivalent (mtoe) (Figure 2). In preparing *WEO 2007*, the IEA also developed an Alternative Policy

Scenario that projects global energy market evolution if developed countries were to adopt all of the energy-security and climate-change policies they are currently considering and if developing countries followed a less energy-intensive development path. Under this scenario, global primary energy demand over the period 2005 to 2030 increases by 38.1% to 15 783 mtoe, some 1 938 mtoe below the Reference Scenario (IEA, 2007c). In the Reference Scenario, fossils fuels account for 82.0% of global energy demand in 2030, compared to 80.9% in 2005. Under the Alternative Policy Scenario, fossil fuels still account for 76.4% of global primary energy demand. The reduction of fossil fuel's share is primarily the result of an overall energy demand reduction with a greater role for nuclear and renewables; in the Alternative Policy Scenario, hydro, biomass, waste and other renewables are 308 mtoe higher in 2030 than in the Reference Scenario and nuclear is 226 mtoe higher.

Coal retains its importance in both scenarios. In the *WEO 2007* Reference Scenario, coal consumption increases from 2 892 mtoe in 2005 to 4 994 mtoe in 2030, an annual rate of increase of 2.2%; in the Alternative Policy Scenario, coal consumption is 3 700 mtoe in 2030, a rate of increase of 1.0% per year over the period 2005-2030. In the Reference Scenario, coal's importance in global primary energy demand increases from 25.3% in 2005 to 28.2% in 2030; in the Alternative Policy Scenario, coal's role declines modestly to 23.4% (Figure 2). It is precisely because of the growing energy needs of the developing world that most forecasts predict a continuing key role for coal in the future energy mix, regardless of climate change policy.

### Table 1. Comparison of world energy consumption growth rates by fuel to 2015 (average annual % growth)

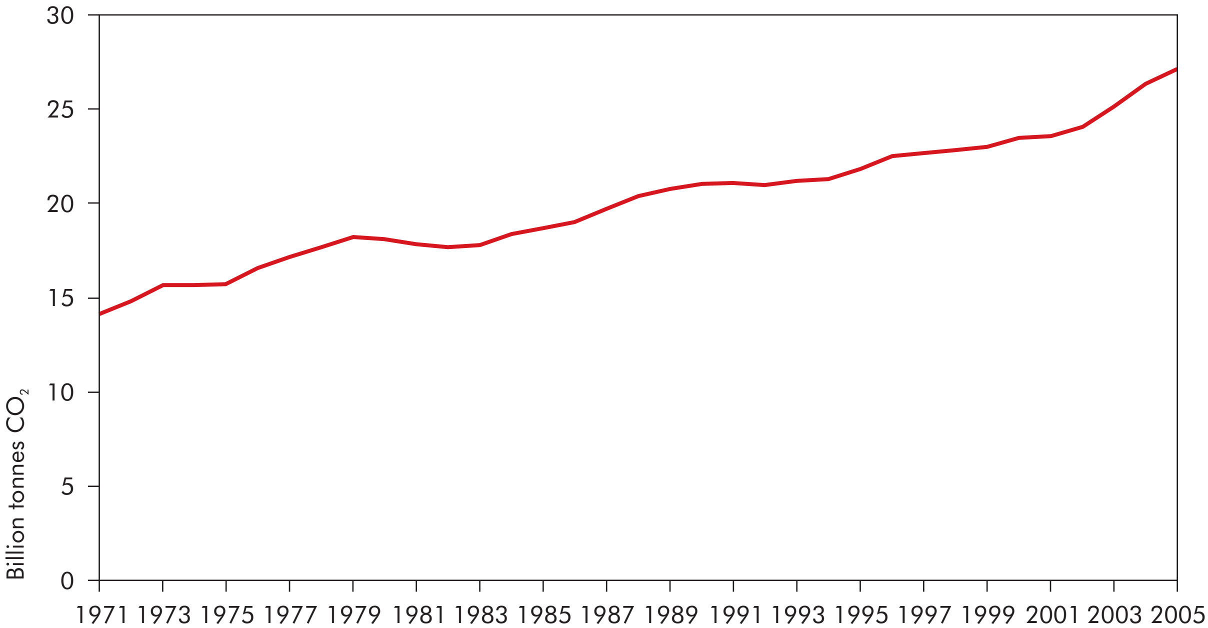
| Fuel | EIA *IEO 2007* (2004-15) | | | IEA *WEO 2007* (2005-15) |
|---|---|---|---|---|
| | Low Growth Case | Reference Case | High Growth Case | Reference Scenario |
| Liquids | 1.2 | 1.5 | 1.9 | 1.7 |
| Natural gas | 2.0 | 2.4 | 2.7 | 2.6 |
| Coal | 2.2 | 2.6 | 2.9 | 3.3 |
| Nuclear | 1.5 | 1.5 | 1.6 | 1.1 |
| Renewables/other | 2.1 | 2.3 | 2.6 | 2.1 |
| **Total** | **1.8** | **2.1** | **2.4** | **2.3** |

Sources: EIA, 2007 and IEA, 2007c.

The *WEO 2007* forecast may be compared with the latest energy forecasts issued by the Energy Information Administration (EIA) of the United States Department of Energy (DOE) in its *International Energy Outlook 2007 (IEO 2007)* of May 2007. In the Reference Case, world marketed energy consumption rises from 447 quadrillion British thermal units (Btu) (11 264 mtoe) in 2004 to 702 quadrillion Btu (17 690 mtoe) in 2030, an increase of 57% or 1.8% per year (EIA, 2007). In *IEO 2007*, the role of coal increases in 2030 compared to 2004, from 25.6% of world marketed energy to 28.4%. In the shorter term to 2015, the EIA projects an annual demand growth for coal of 2.6% (2.2% in the Low Growth and 2.9% in the High Growth Cases). This is a decrease from the 3.1% in *IEO 2006* and is significantly lower than the *WEO 2007* forecast growth for coal of 3.3% (Table 1).

All of the energy growth forecasts have major $CO_2$ emission consequences. The *WEO 2007* Reference Scenario sees $CO_2$ emissions increase from 26.6 gigatonnes $CO_2$ ($GtCO_2$) in 2005 to 34.1 $GtCO_2$ in 2015 and 41.9 $GtCO_2$ in 2030. In the *WEO 2007* Alternative Policy Scenario, emissions rise to 31.9 $GtCO_2$ in 2015 and 33.9 $GtCO_2$ in 2030. In the *IEO 2007* forecast, $CO_2$ emissions in the Reference Case increase from 26.9 $GtCO_2$ in 2004 to 33.9 $GtCO_2$ in 2015 and 42.9 $GtCO_2$ in 2030. Both the IEA and EIA forecasts may be optimistic in terms of $CO_2$ emissions growth projections. In fact, global $CO_2$ emissions have increased much more rapidly in the past half decade than during the 1990s (Figure 3). Global $CO_2$ emissions rose from 23.5 $GtCO_2$ in 2000 to 27.1 $GtCO_2$ in 2005 (IEA, 2007d). Some forecasts for 2006 project emissions already exceed 30 $GtCO_2$, reflecting a rise in energy consumption that is well above any of the long-term trends described in the forecasts cited here (Canadell *et al.*, 2007).

**Figure 3. Global $CO_2$ emissions from fossil fuel combustion, 1971-2005**




Source: IEA, 2007d.

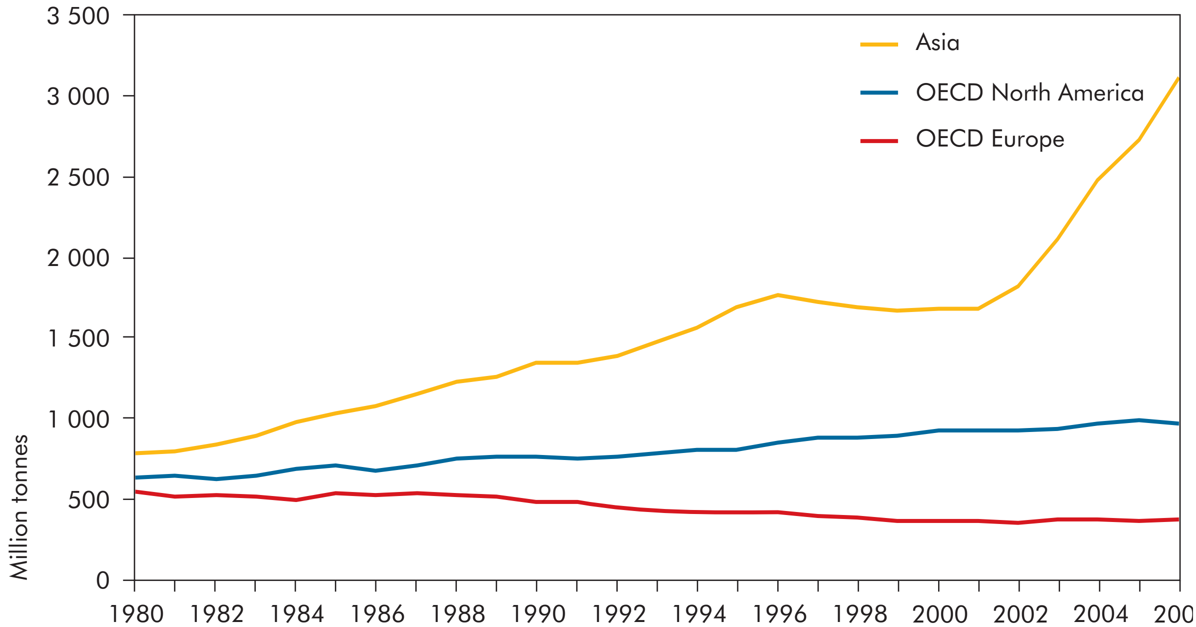
Because of its abundance, broad geographic distribution and comparatively low and stable delivered cost, coal will remain a key component of the electricity generation fuel mix for most of this century, unless there are major breakthroughs in alternative energy technologies. Global proved reserves for all types of coal are 909 billion tonnes, of which 41.1% are located in Organisation for Economic Co-operation and Development (OECD) member countries (BP, 2007). In contrast, OECD countries have 6.6% of the world's oil reserves and 8.8% of the natural gas reserves (*ibid.*). In electricity generation, coal plays a crucial role: in the OECD in 2005, coal supplied 38% of generation and renewables 3%; in North America coal was 44.9% of electricity production and renewables 2.4% (IEA, 2006b). The growth in global coal consumption has accelerated in the decade 1995-2005: up 36% worldwide and over 70% in Asia (*ibid.*). Coal's share of primary energy consumption has declined in Europe but increased in Asia. While hard coal consumption has declined slowly in Europe over the past quarter century and increased gradually in North America, in Asia consumption has increased by almost 300% slowing only for a few years after the 1997 Asian financial crisis (Figure 4). The rapid rise of Asia's economies has been, above all, powered by coal and coal demand will likely rise strongly as Asian countries continue to raise living standards (Figure 5). The *BP Statistical Review of World Energy* reveals that in the period 2001-2006, coal consumption in the Asia-Pacific region increased by 642.1 mtoe, accounting for some 91% of the global increase in coal consumption during that period.

China leads global growth. It has embarked on campaigns to close older, smaller coal-fired stations and has indicated its desire for the future to primarily build supercritical units of 600 MW or above[1]. In 2005, about

1 For previous efforts to close small coal plants, see article in *China Daily*, October 9, 2003, www.chinadaily.com.cn/en/doc/2003-10/09/content_270086.htm; also *China Daily*, November 26, 2000. For the current effort to close small coal plants, see Platts *International Coal Report*, March 5, 2007, p. 13.

70 GW of new generation came online in China. In 2006, the comparable figure was 102 GW, of which 89% was coal. For 2007, a further 90 GW are expected[2]. Longer term, the goals are even more ambitious. A vice-minister of the National Development and Reform Commission (NDRC) indicated that, by 2025, China's power consumption could reach 11 000 terawatt hours (TWh) with a generating capacity of 2 400 GW[3], increases of 330% and 360%, respectively, from current levels. Although these figures are significantly above other forecasts, coal could make up about 78% of the generation mix by 2030 with nuclear at 3%, natural gas at 4%, hydro at 12% and renewables at 3% (IEA, 2007c).

**Figure 4. Global hard coal consumption by major region, 1980-2006**




Source: IEA, 2007e.

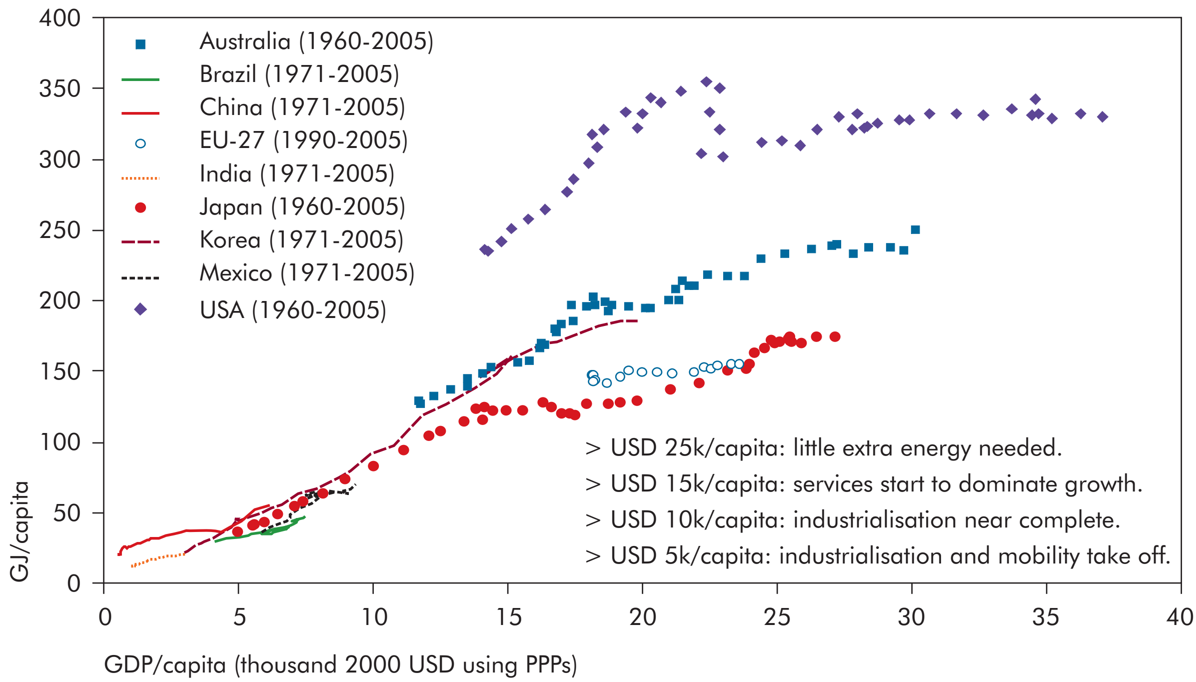
In India, after several years of 8% annual GDP growth, the unmet demand for more electricity is large. The Government of India has announced six "ultra-mega" projects of 4 000 MW each, four using imported coal and two using domestic coal, while Reliance Industries has announced plans for a 12 000 MW plant (the world's largest) to run on domestic coal. Additional coal-fired capacity has been announced by many developing countries in Asia, including Bangladesh, Cambodia, Indonesia, Malaysia, Myanmar, Pakistan, South Korea, Sri Lanka, Thailand and Vietnam[4].

2 *Financial Times*, February 7, 2007 citing *China Electric Power News*. The growth in 2006 seems to have occurred outside the view of central government officials. Late in 2006, these reported that the total new capacity to be commissioned in 2006 would be about 80 GW, see *China Electric Power Weekly*, November 2, 2006, p.1.

3 See *China Daily*, October 19, 2004, *Official Calls for More Power Stations*, quoting Zhang Guobao, Vice-minister, NDRC, www.chinadaily.com.cn/english/doc/2004-10/19/content_383600.htm. These figures are far larger than those projected for China in *WEO 2007* for 2030: 8 472 TWh electricity generation and a capacity of 1 775 GW (p.597). Indicative of the magnitude of some of the expansion projects are the ambitions of Inner Mongolia to build 100 GW of lignite-fired power by 2010 (current capacity is 1 400 MW) to exploit its estimated 139.3 billion tonnes of lignite reserves (see Platts *International Coal Report*, December 11, 2006, p.12).

4 For 21.7 GW of new coal-fired capacity for the period 2007-2021, see Platts *International Coal Report*, February 12, 2007, p.13; for fourteen new coal plants planned for South Korea by 2020, see *ibid.*, January 8, 2007, p.10; for Sri Lanka, see *ibid.*, January 8, 2007, p.4; for Vietnam, see *ibid.*, November 27, 2006, p.9 and November 13, 2006, p. 14; for Cambodia and Myanmar, see *ibid.*, August 7, 2006, p.4; for the investment plans of Shenhua Group in Pakistan, see *ibid.*, November 13, 2006, p. 15.

**Figure 5. Historical relationship of per capita GDP and energy demand growth**




Source: IEA, 2007d.

In southern Africa, economic growth and energy demand have also accelerated as resource-dependant economies retain more value-added work. Energy-intensive, processing and refining plants for minerals and ores have added to electricity demand. New coal-fired electricity generation capacity is under construction in the Republic of South Africa, and under consideration in other southern African nations, such as Botswana and Mozambique[5]. In the north of Africa, Morocco's rising power demand is to be met by a doubling of existing coal-fired capacity. In South America, a sharp reduction in pipeline gas supplies from Argentina has led to plans for a number of new coal projects in Chile[6].

In Europe, new coal-fired power plant activity is focused primarily in the East with large new lignite projects tendered or under construction in Turkey, Kosovo, Bosnia and Bulgaria[7]. Ukraine, which was deeply shaken by a dispute with Russia in January 2006 over natural gas supplies, is planning a large increase in power sector coal consumption[8]. Russia also intends to increase its coal-fired generation share from 27% in 2006 to 29% in 2010 and 37% in 2015 in order to leave more gas available for export[9].

5 For new coal-fired capacity planned by Eskom, see Platts *International Coal Report*, October 16, 2006, pp.1, 9; however, natural gas capacity is also to be added, see Platts *International Gas Report*, February 12, 2007, p.5; for Mozambique, see Platts *International Coal Report*, August 28, 2006, pp.10-11; for the 2 400 MW Mmamabula project in Botswana, see *ibid.*, October 23, 2006, pp.7-8.

6 A 500 MW project by BHP Billiton, Platts *International Coal Report*, November 13, 2006, p.14; 250 MW planned by AES Gener, *ibid.*, August 28, 2006, pp.4-5; 350 MW by Endesa Chile, *ibid.*, July 31, 2006, p.15; and 400 MW by Suez, *ibid.*, June 26, 2006, p.7.

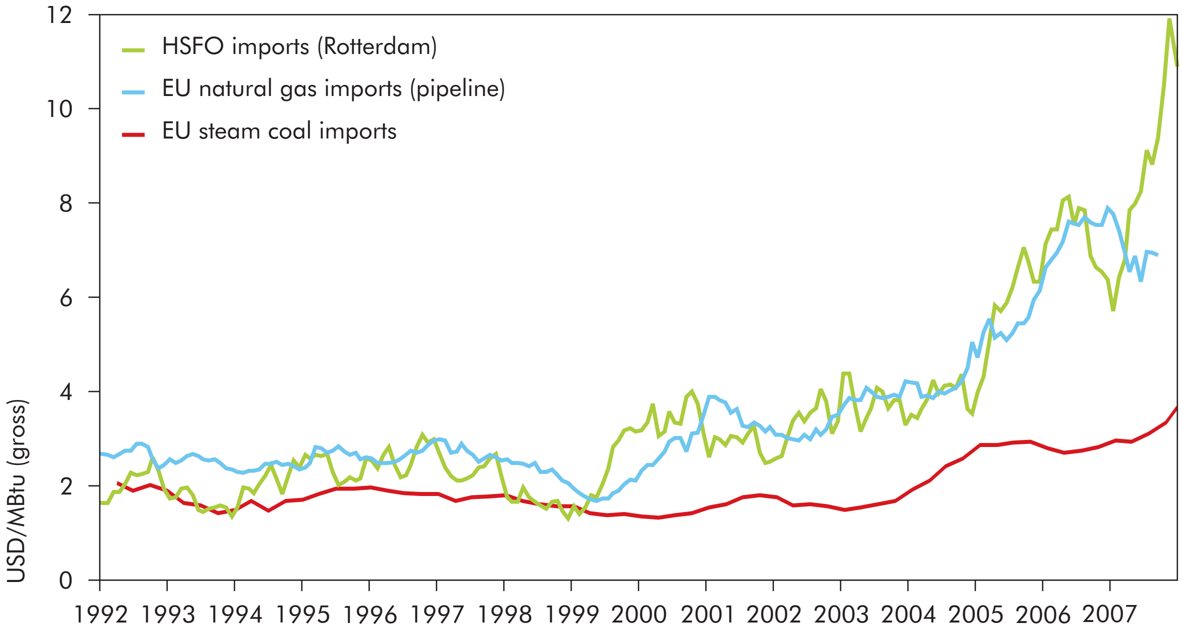
7 For Turkey's Afsin-Elbistan projects, see Platts *International Coal Report*, August 28, 2006, p.9; for Kosovo, see Platts *Energy in East Europe*, January 5, 2007, p.15; for Bosnia, see *ibid.*, January 19, 2007, p.9; and for the various Maritza projects in Bulgaria, see *ibid.*, March 2, 2007, p.3.

8 Platts *International Coal Report*, December 18, 2006, p.9; a 2006 IEA report on Ukraine indicates that coal production may rise by up to 50 million tpa between 2005 and 2030, see *Ukraine: Energy Policy Review 2006*, IEA, Paris, pp.245-246.

9 Platts *Energy in East Europe*, February 16, 2007, pp.1-2; *ibid.*, p.3 a separate report quoting President Putin to the effect that *"coal should become the main fuel for Russian power plants"*; *ibid.* March 2, 2007, p.16 on three new coal-fired power plants announced by OGK-5; for the greater use of coal in electricity generation in the future, see also *Russia Energy Survey 2002,* IEA, Paris, 2002, pp.200-202, 256.

Substitution of coal by other energy sources has faltered due to cost and supply constraints. Political instability in some major oil-exporting regions has greatly heightened concerns about the security of imported oil supplies and contributed to high oil prices. In some regions, oil-price linkages have led also to high natural gas prices; these have raised risk and lowered confidence about utilities' access to natural gas supplies at reasonable prices (Figure 6).

**Figure 6. Trends in European import prices for steam coal, pipeline natural gas and high sulphur fuel oil (HSFO), 1992-2007**




Source: IEA data.

Interruptions to supply in 2005 and 2006, caused by extreme weather and political disputes, brought the increasing dependence on natural gas in some countries into sharp focus. Furthermore, it is clear that as natural gas moves more into power generation and less into the heating market, a structural shift to high-price levels may occur[10]. In fact, the Gas Exporting Countries Forum, which represents countries controlling in excess of 70% of global gas reserves (Algeria, Bolivia, Brunei, Egypt, Indonesia, Iran, Libya, Malaysia, Nigeria, Oman, Qatar, Russia, Trinidad and Tobago, the UAE and Venezuela), has announced the establishment of a high-level group to examine the future outlook for natural gas prices. In any event, consumption of both natural gas and oil add to GHG emissions. It is impossible that a wholesale switch to other fossil fuels will achieve the stringent GHG emission cuts suggested in the current national and international dialogue without the existence of commercially viable CCS.

Coal use can be influenced not only by the availability of natural gas and oil, but also of renewable energy, particularly wind and biomass. Much of the growth in renewable energy is expected to take the form of an increase in wind power. The primary issue with wind power is that it is intermittent and cannot follow load. Experience with onshore electricity generation from wind is that it has annual load factors lower

10 For the argument that gas suppliers will seek to capture the economic rent from lower $CO_2$ emissions as power prices are set by higher emitting brown coal plants, see LBD-Beratungsgesellschaft mbH, *Langfristige Erdgasverstromung*, GEE Symposium, November 24, 2003, www.gee.de/old/kraftwerke_03/schlemmermeier.pdf.

than anticipated, typically 18-20%, and that wind peaks seldom match electricity demand peaks[11]. The intermittent and distributed nature of wind power require substantial additional investments in reserves of conventional generation and electricity transmission grids[12]. While experience with onshore wind generation has shown capital costs reducing by approximately 2% per year[13], offshore facilities have substantially higher capital and maintenance costs, particularly when they are located in deep water (Vahrenholt, 2006, pp.70-71). The deployment of renewable energy has succeeded with substantial public subsidy and regulatory support, but it can only be a part of a greater effort to achieve the rapid reduction of GHG emissions needed to meet the commitments suggested by national and international leaders.

Nuclear energy, which currently provides about 15% of total world electricity, continues to expand slowly, but is plagued by long lead times and apprehension about the security of nuclear fuel supply and waste processing. Since the inception of nuclear power in the mid-1960s, average construction time has increased and, faced also with long design, review and permitting times, investors have become cautious. There are currently about 28 GW of nuclear capacity under construction or undergoing refurbishment in thirteen countries[14]. Though the capital costs of all electricity generation technologies have risen sharply over the last five years, nuclear plant costs are difficult to estimate and cost overruns are not unusual. While the nuclear industry has made good progress in standardising designs for a new generation of reactors, there is no evidence that nuclear power alone could result in enough GHG emission reductions to meet the timing and magnitude of those proposed by national and international leaders in the near term.

11 White, D., *Reduction in Carbon Dioxide Emissions: Estimating the Potential Contribution from Wind Power,* December 2004, pp.2-4 (sponsored by Renewable Energy Foundation); *Renewable Energy: The Need for Balance and Quality*, Renewable Energy Foundation, 2005, pp.29-37. A 2006 study, using an assumed generating base of 25 GW distributed evenly over the UK and hourly wind data from 1995-2006, showed that power swings of 70% in 30 hours were the norm in January and that the average minimum output was 3.7%, see Oswald Consultancy Ltd., *25 GW of Distributed Wind on the UK Electricity System*, an engineering assessment carried out for the Renewable Energy Foundation, December 7, 2006, Oswald Consultancy Ltd., Coventry, UK.

12 The UK National Audit Office estimates that, by 2010, such grid upgrades will cost GBP 1.1-1.3 billion, see *Department of Trade and Industry – Renewable Energy*, February 11, 2005, The Stationery Office, London, p.3; for the period 2010 to 2020 costs have been estimated to range between GBP 150 and GBP 400 million per year for a 20% renewables target, depending on technology and location, see Strbac, G., *Quantifying the System Costs of Additional Renewables in 2020*, October 2002, ILEX Energy Consulting, Oxford, UK, pp. 6-8.

13 *Wind Power Monthly*, April 2003, p.51.

14 World Nuclear Association database accessed January 14, 2008, www.world-nuclear.org.

# THE PATHWAY TO CARBON DIOXIDE CAPTURE AND STORAGE (CCS)

For the ambitious GHG reduction targets, set in the latest IPCC reports and elsewhere, to be achieved, near-zero emission technologies must be applied to nearly all large stationary sources, including fossil fuel-fired power plants, large steel mills, oil refineries and chemical plants by 2050. Moreover, these technologies need to be economically viable in both the developed and developing world. Given the high-growth trajectory of energy consumption in developing economies, it will be difficult to achieve these targets without significantly accelerating the deployment of large-scale GHG emission reduction technologies. Setting these new goals means that the performance priorities for clean coal technologies (CCTs) need to be altered.

Indeed, the coal sector – producers, consumers and equipment suppliers – as well as governments and agencies in countries where coal is essential, have a long experience of stimulating the deployment and financial viability of technologies to reduce various emissions from coal use. These have included technologies to control particulates, sulphur dioxide, other smog precursors and mercury, technologies that continue to be deployed in both developed and developing economies.

The past imperative to accelerate the spread of CCTs is similar to the current imperative to reduce GHG emissions and contain the temperature rise effects of global climate change. These efforts are ongoing, and deployment of CCTs in the developing world is a critical part of the overall effort. The coal sector is already reducing its GHG "footprint" by stimulating deployment of more efficient combustion technologies. Experience gained with earlier and current CCTs provides a pathway for a more dramatic response to meet the GHG emission reduction targets proposed by national and international leaders. This needs to be followed with CCS technologies – for as the MIT study concludes, *"… the priority objective with respect to coal should be the successful large-scale demonstration of the technical, economic, and environmental performance of the technologies that make up all of the major components of a large-scale integrated CCS system – capture, transportation and storage."* (MIT, 2007, p. xi).

Accelerated deployment of CCS is becoming more likely due to endorsements by recent major studies. In late 2005, an IPCC Special Report noted that CCS was a good technology to apply to large, single-point sources of $CO_2$, including natural gas- and coal-fired power plants as well as biomass energy facilities, natural gas production, fossil fuel-based hydrogen production plants, synthetic fuel plants and major $CO_2$ emitting industries such as cement, oil refining, petrochemicals and iron and steel (IPCC, 2005). Also in 2005, the G8 Summit at Gleneagles requested that the IEA and the Carbon Sequestration Leadership Forum (CSLF) study definitions, costs and scope for "capture-ready" plant and consider economic incentives. The summit leaders recommended research on the options for geological storage of $CO_2$ (G8, 2005).

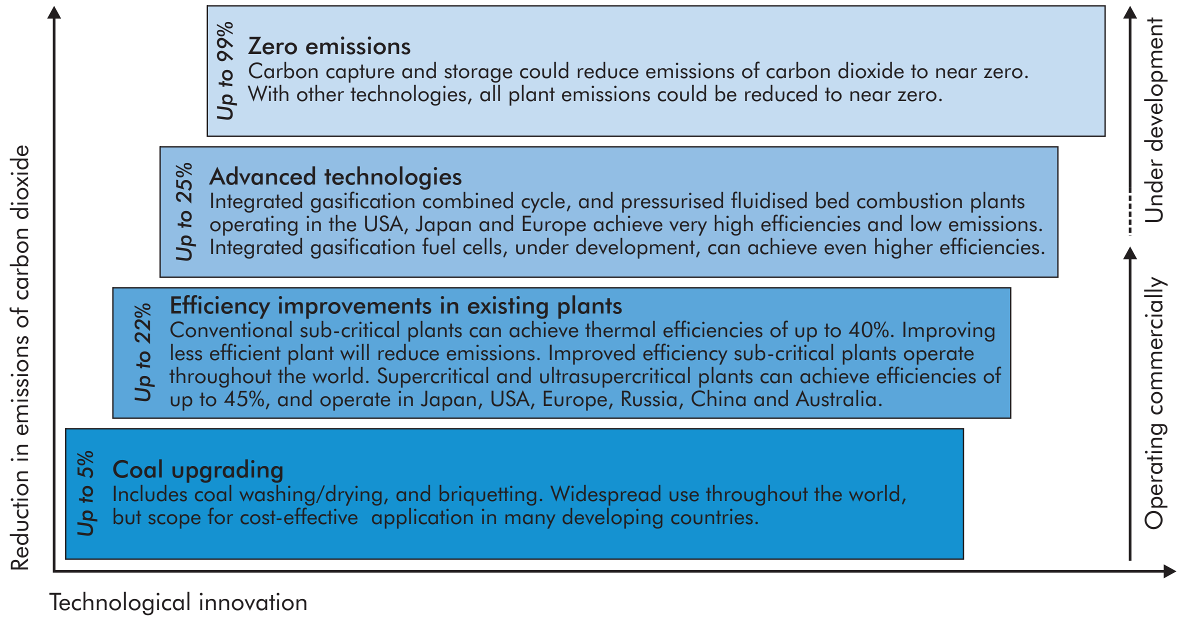
The IEA has noted that the cost of CCS is estimated to be between USD 40 and USD 90 per tonne of $CO_2$ captured and stored; and that with the most cost-effective technologies, capture costs are as low as USD 20-40 per tonne of $CO_2$ (IEA, 2006a). Transport would add as much as a further USD 10/tonne. The IEA concluded that the future cost for CCS will depend on which technologies are used, how they are applied and how far costs fall as a result of R&D and learning realised during market uptake (Table 2).

*The Stern Review* noted that, *"CCS technologies have the significant advantage that their large-scale deployment could reconcile the continued use of fossil fuels over the medium- to long-term with the need for deep cuts in emissions"* (Stern, 2007, p. 250). Stern observed that the global electricity sector needed to be largely decarbonised by 2050, with CCS, nuclear and renewables, and emphasised that CCS could, *"… effectively reduce emissions from the flood of new coal-fired power stations planned over the next decades, especially in India and China"* (Stern, 2007, pp. 235 & 250).

A number of features of CCS technologies, noted by the IPCC, the IEA and *The Stern Review*, make them particularly attractive:

- CCS technology is not limited to power production, but can be used to mitigate $CO_2$ emissions from chemical plants, steel mills, oil refineries and petrochemical plants.
- Where there are old and depleted oil fields, the use of $CO_2$ for enhanced oil recovery (EOR) offers a dual advantage of sequestering GHGs and increasing oil resource recovery; enhancement of coalbed methane recovery through $CO_2$ injection offers similar benefits.
- CCS technology has the potential to actually remove carbon dioxide from the atmosphere by growing biomass for energy production purposes and capturing the $CO_2$ released when it is burned or otherwise utilised (Obersteiner, 2002).

## Figure 7. Reductions in emissions of $CO_2$ through clean coal technological innovation




Source: IEA, 2004.

The IEA has identified four groups of CCTs which have the capability to dramatically reduce $CO_2$ emissions from coal-fired generation (Figure 7):

- Coal upgrading
- Efficiency improvements at existing power plants

## Table 2. IEA estimates of CCS costs for current and prospective generating technologies

| Fuel & Technology | Starting year | Investment cost (USD/kW) | Efficiency (%) | Efficiency loss (%) | Additional fuel (%) | Capture efficiency (%) | Capture cost (USD/t $CO_2$) | Electricity cost (UScents/kWh) | Electricity cost reference plant (UScents/kWh) | Additional electricity cost (UScents/kWh) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Likely technologies** | | | | | | | | | | |
| Coal, steam cycle, CA | 2010 | 1 850 | 31 | -12 | 39 | 85 | 33 | **6.79** | 3.75 | 3.04 |
| Coal, steam cycle, membranes + CA | 2020 | 1 720 | 36 | -8 | 22 | 85 | 29 | **6.10** | 3.75 | 2.35 |
| Coal, USC steam cycle, membranes +CA | 2030 | 1 675 | 42 | -8 | 19 | 95 | 25 | **5.70** | 3.75 | 1.95 |
| Coal, IGCC, Selexol | 2010 | 2 100 | 38 | -8 | 21 | 85 | 39 | **6.73** | 3.75 | 2.98 |
| Coal, IGCC, Selexol | 2020 | 1 635 | 40 | -6 | 15 | 85 | 26 | **5.71** | 3.75 | 1.96 |
| Gas, CC, CA | 2010 | 800 | 47 | -9 | 19 | 85 | 54 | **5.73** | 3.75 | 1.98 |
| Gas, CC, Oxyfueling | 2020 | 800 | 51 | -8 | 16 | 85 | 49 | **5.41** | 3.75 | 1.66 |
| Black liquor, IGCC | 2020 | 1 620 | 25 | -3 | 12 | 85 | 15 | **3.35** | 2.35 | 1.00 |
| Biomass, IGCC | 2025 | 3 000 | 33 | -7 | 21 | 85 | 32 | **10.06** | 7.46 | 2.60 |
| **Technologies under development** | | | | | | | | | | |
| Coal, CFB, chemical looping | 2020 | 1 400 | 39 | -5 | 13 | 85 | 20 | **5.26** | 3.75 | 1.51 |
| Gas, CC, chemical looping | 2025 | 900 | 56 | -4 | 7 | 85 | 54 | **5.39** | 3.75 | 1.64 |
| Coal, IGCC & SOFC | 2035 | 2 100 | 56 | -4 | 7 | 100 | 37 | **6.00** | 3.75 | 2.25 |
| Gas, CC & SOFC | 2030 | 1 200 | 66 | -4 | 6 | 100 | 54 | **5.39** | 3.75 | 1.64 |

Note: The above comparison is based on a 10% discount rate and a 30-year process lifespan. The investment costs exclude interest during the construction period and other owner costs, which could add 5-40% to overnight construction cost. This approach has been applied to all technologies that are compared in the study. Coal price = USD 1.5/GJ; Natural gas price = USD 3/GJ. $CO_2$ product in a supercritical state at 100 bar. $CO_2$ transportation and storage is not included. Capture costs are compared to the same power plant without capture. CA = Chemical Absorption. CC = Combined-cycle; CFB = Circulating Fluidised Bed; IGCC = Integrated Gasification Combined-cycle; SOFC = Solid Oxide Fuel Cell; USC = Ultra Supercritical.

The IGCC data for 2010 refers to a European highly-integrated plant based on a Shell gasifier, while the 2020 data refers to a less integrated US design based on an E-gas gasifier. The efficiency remains at the same level because new gas turbines will become available in the 2010 to 2020 period (the so-called 'H-class') and result in an increase in efficiency. The gasifier substitution reduces capture efficiency losses and reduces investment cost penalties. Assuming 4% fixed operation and maintenance cost, the electricity cost can be calculated by the formula: Electricity cost = (Investment cost x (0.11+0.04)/31.54/Availability Factor + Fuel price/Efficiency) x 0.036.

Source: IEA, 2006a.

- Advanced technologies (e.g. IGCC)
- Near-zero emission technologies

In addition to these four CCT categories, the CIAB has added a fifth for the purpose of this report, **$CO_2$ transport and storage**. The range and complexity of these five groups suggests a pathway or experience curve which builds upon ongoing efforts to improve fuel combustion efficiency and pollution control equipment performance, whilst moving to research, develop and deploy more advanced systems for carbon dioxide capture and storage.

## Coal Upgrading

While three of the four CCT groups do not provide the potential to reach the targets of the IPCC and others, driving their application is important because they do provide immediate emission reductions and a pathway for the most effective technology – near-zero emissions with CCS. It is estimated that coal washing/drying and briquetting could reduce $CO_2$ emissions by as much as 5%. This involves the application of established, commercial technologies, in use in the USA, Europe, Japan and Australia, but not yet widely deployed in the developing world or the former Soviet Union.

## Efficiency Improvements at Existing Power Plants

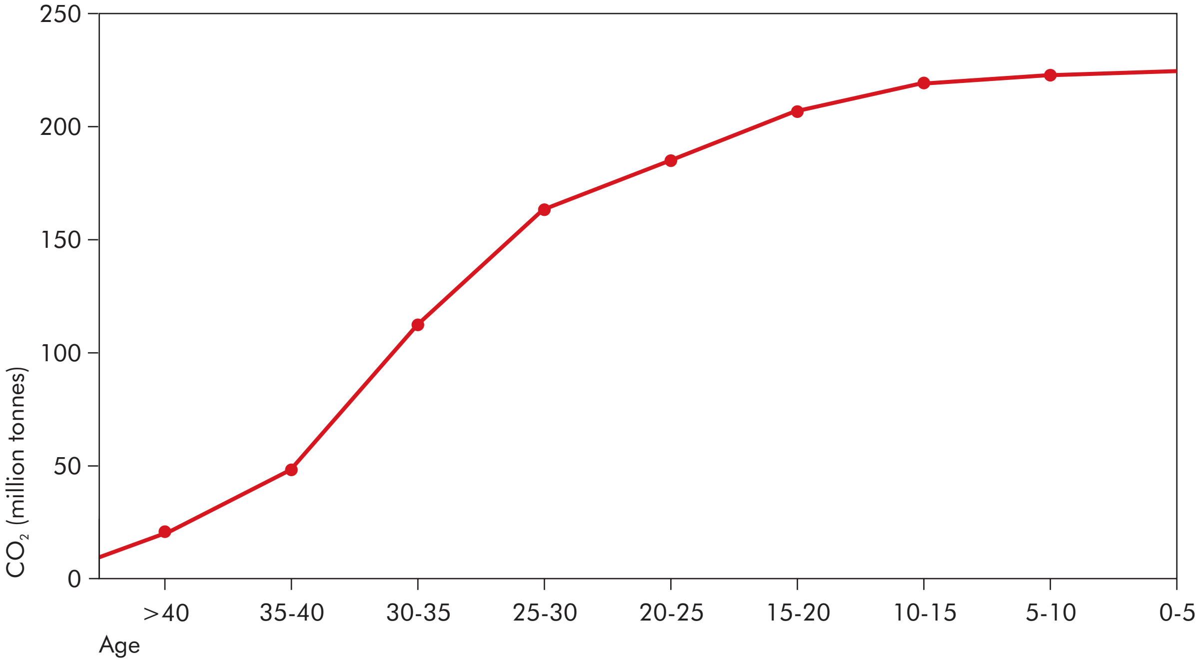
The World Coal Institute has noted the scope for efficiency improvements at existing power plants, where achieving thermal efficiencies of up to 40% could reduce $CO_2$ emissions by as much as 22%, especially in non-OECD countries (WCI, 2003). This potential is validated by the improvements achieved and projected in EU countries (Figure 8). In developing countries, funding for such improvements, which should include equipment upgrading and the systematic performance monitoring and diagnostic testing of boilers, turbines, condensers, and auxiliary equipment, could come from a combination of development aid, export credits and electricity revenues (NETL, 2001). The global potential to reduce $CO_2$ emissions through efficiency improvements at existing power plants is the subject of a forthcoming IEA report for the G8. The CIAB has advised on the complexity of determining power plant efficiency and noted that, for comparisons to be valid, they must account for local conditions and fuel quality.

## Advanced technologies

Research and development in support of supercritical (SC) and ultra-supercritical (USC) technologies has allowed their deployment for new construction such that they are now considered mainstream for power generation. There is a growing base of high-efficiency supercritical coal-fired units in operation. Supercritical status for hard coal plants is defined as achieving outlet steam temperatures of 540-566°C (1 000-1 050°F) and a pressure of 250 bar (3 600 psi). Ultra-supercritical units are defined as those with outlet steam temperatures above 590°C (1 100°F) and pressures above 250 bar. Using data from the IEA Clean Coal Centre, the World Coal Institute estimates that there are over 240 supercritical units and 24 USC units in operation worldwide (WCI, 2006). In the future, higher operating temperatures, of up to 700°C (1 300°F), should allow even higher efficiencies to be achieved (Figure 9). Programmes to develop the materials and fabrication techniques for boilers, pipework, valves and turbines to operate at these temperatures are well advanced.

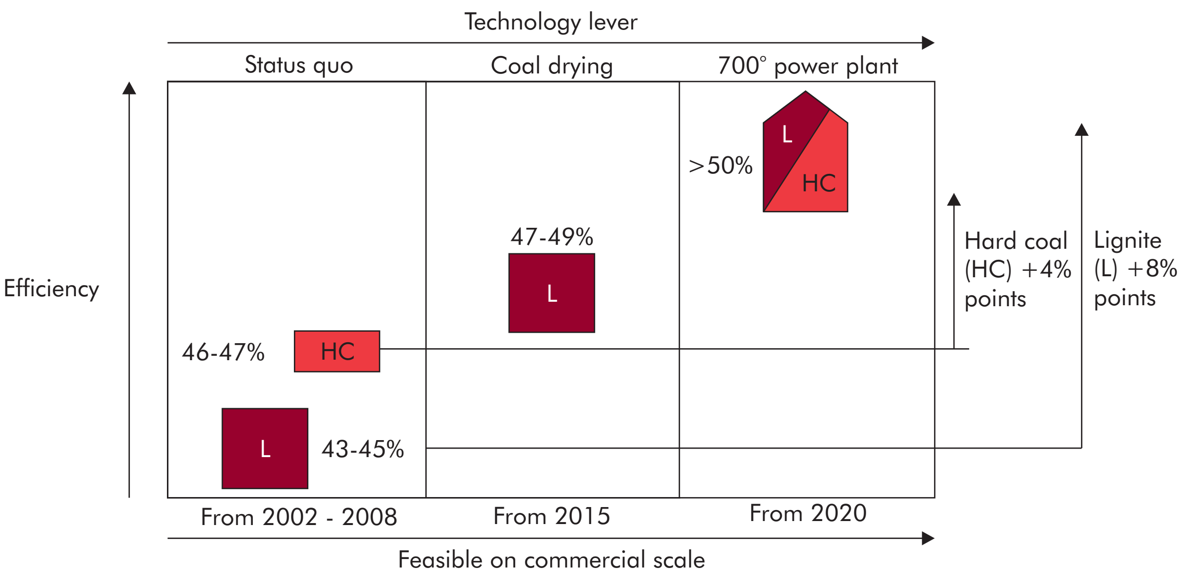
The effort to reduce emissions by deploying highly efficient, pulverised coal plants has been driven by a combination of research, development and deployment funded by government and industry consortia and supported by favourable regulatory treatment. In Japan, the USA, Germany, Denmark and other countries, national governments, multilateral agencies, power utilities, coal suppliers and equipment manufacturers have co-operated to fund materials research, equipment design and controls development that has enabled new plants to achieve 43%-47% efficiency. Important advantages are that smaller amounts of $CO_2$ per unit of electricity generated will have to be captured when CCS is applied to these high-efficiency power plants, and that the efficiency, cost and resource usage penalties of $CO_2$ capture will become lower for future SC and USC power plants as the trend to higher efficiencies continues, with efficiencies above 50% now in sight.

**Figure 8. Cumulative $CO_2$ emission reduction potential in the EU from efficiency improvements at existing power plants of all ages**




Source: Euracoal, 2005.

**Figure 9. Development phases for power plant efficiencies**




Source: Euracoal, 2005.

While coal gasification has been a commercial technology since the 19th century, its integration with combined cycle gas turbines for electricity generation is a CCT path stimulated by joint government-industry research over the last thirty years. While integrated gasification combined cycle (IGCC) has potential to achieve higher efficiency than SC or USC pulverised coal boilers, the systems are just entering the dawn of commercialisation, and further research, development and operating experience is necessary before the technology can reach the scale and reliability needed for economic competitiveness. Nevertheless, commercial-scale facilities in the Netherlands, Spain and the USA are operating successfully and providing operational experience with the technology. Advantages of gasification include the flexibility to handle a variety of feed stocks (e.g. coal, biomass, petcoke and oil tars), and also having the option to produce multiple products (e.g. electricity, chemicals, hydrogen, transport fuels and synthetic natural gas).

The CIAB notes that the CDM Executive Board of the United Nations Framework Convention on Climate Change (UNFCCC) approved a consolidated methodology in September 2007 for new, grid-connected fossil fuel-fired power plants using less GHG-intensive technology that enables them to sell carbon offsets under the Kyoto Protocol's Clean Development Mechanism (CDM). Under the rules, power plants in developing countries may be eligible to sell the offsets if they utilise the CCTs mentioned above.

## Near-zero Emission Technologies

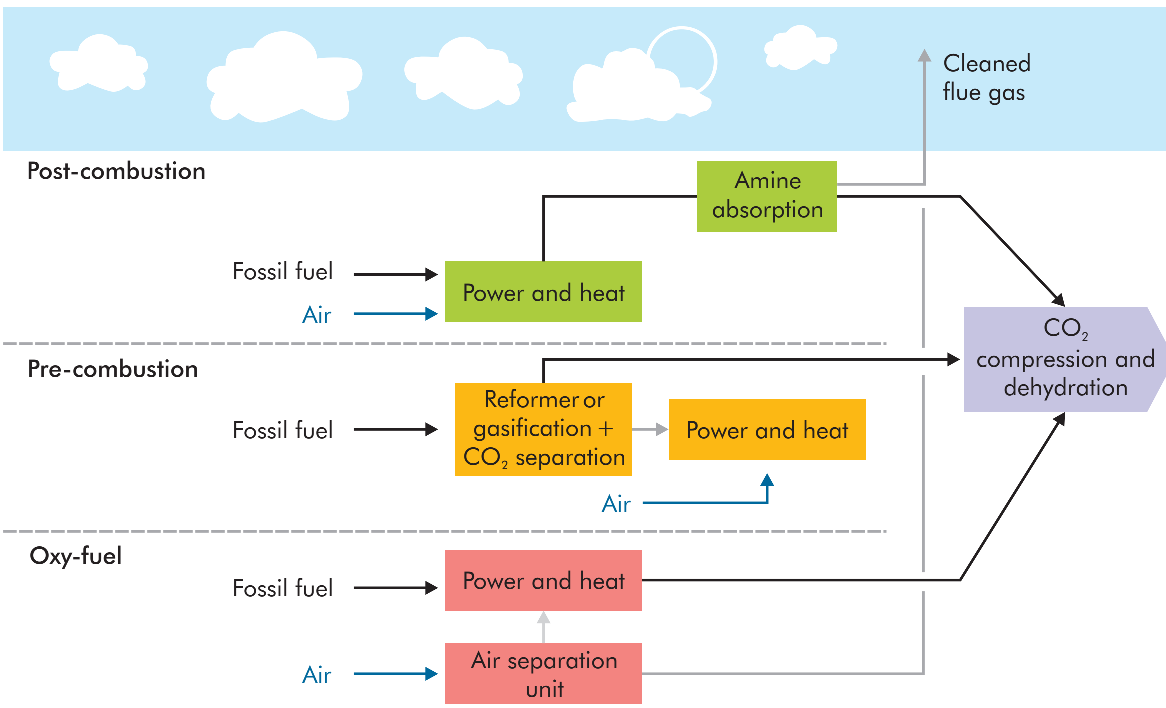
Up to the mid-1990s, before global climate change gained a high profile, CCT drivers were aimed primarily at the first three tiers of technologies identified by the IEA in Figure 7. Subsequent to the signing of the Kyoto Protocol in 1997, attention shifted from controlling emissions of particulates, sulphur dioxide, smog precursors and mercury, to efficiency and $CO_2$ capture and storage. Although many CCT projects – especially in developing countries – continue to target conventional pollutant emissions, the focus of CCT development in OECD countries has turned to "near-zero" emission technologies intended to decarbonise coal combustion. The research, development and deployment effort for these systems is in progress, with some governments, multilateral agencies and industrial entities taking steps to move their focus away from conventional pollutant emissions and economic performance, to a focus on meeting GHG emission reduction targets. In Australia, for example, the black coal industry has created an AUD 1 billion fund, through a voluntary levy on coal production, which will fund the demonstration of low-emission technologies over the next ten years. Demonstration projects already funded include oxy-fuel and post-combustion capture. Many other projects, small and large, are in progress around the world, including in China and other developing countries.

Figure 10 illustrates the technology options available for $CO_2$ removal, with the three main approaches to $CO_2$ capture for power plant applications: post-combustion systems separate $CO_2$ gas produced by "air-blown" combustion of any fossil fuel or biomass; pre-combustion systems process the primary fuel in a reactor or gasifier to produce synthesis gas (syngas) which is then converted and separated into two gas streams – $CO_2$ for storage and hydrogen as fuel for a gas turbine, a transport fuel or as chemical feedstock; and oxy-fuel combustion systems, which use "oxygen-blown" combustion to produce a flue gas with a much higher concentration of $CO_2$ than conventional air-blown combustion.

$CO_2$ capture is required in certain industrial processes and has been used for almost a century. For example, $CO_2$ is captured in the purification of natural gas and from the production of hydrogen-containing syngas in the manufacture of ammonia, alcohols and synthetic liquid fuels. Natural gas purification and ammonia production are commercial-scale operations. Indeed, much of the current $CO_2$ storage experience has come from the large-scale disposal of $CO_2$ associated with natural gas production.

$CO_2$ recovery from air-blown fossil fuel combustion involves the separation and capture of $CO_2$, at low concentration, from a flue gas. There are several commercially available process technologies for $CO_2$ capture from flue gases. An absorption process, based on chemical solvents, is currently viewed as the preferred option for post-combustion $CO_2$ capture. At present, this offers the highest capture efficiency, with the lowest energy use and cost, when compared with other post-combustion capture processes. Absorption processes are operated commercially, but have not been applied at the scale required for large coal-fired power plants. Currently, there are a number of international R&D and pilot-scale projects that aim to address performance and scale-up issues. Overall, the status of post-combustion technology is that all of the major components are commercially available, but often at a smaller scale and not integrated or optimised for application at large, coal-fired power plants. Significant issues remain: the process requires very clean flue gas; and release of the absorbed $CO_2$ and regeneration of the absorption solvent involves high parasitic energy losses that badly affect power generation efficiency. An incentive to continue with research and development is that the process has the potential to be retrofitted to existing fossil fuel- and biomass-fired combustion systems. Whether post-combustion systems are part of a new power plant, or retrofitted to an existing power plant, reducing capture costs appreciably is important and this requires identifying absorbents and processes that can effectively capture and release $CO_2$ with a much lower energy penalty.

## Figure 10. Overview of main technology options for $CO_2$ capture from power plants




Source: ZEP, 2006.

Applying pre-combustion $CO_2$ capture to coal gasifiers requires the addition of a shift reactor to produce a mix of hydrogen and $CO_2$, followed by separation of the $CO_2$ and its further compression for transport. Individual components of pre-combustion $CO_2$ capture have been successfully used at scale in industry for many years. As noted above, recent development of gasification, as it applies to power generation (i.e. IGCC), has been targeted towards achieving acceptable reliability and availability.

Research and development needed to advance IGCC to the stage of full CCS includes: development of turbines for hydrogen-rich gas; system integration studies for the co-production of electricity with high-value fuels, chemicals and/or hydrogen; further fuel injection and processing studies to increase the range of coals, lignites and other solid fuels that can be used in gasifiers; and, enhancements of syngas clean-up techniques to improve the efficiency of downstream components and improve the attractiveness of gasification in general.

For oxy-fuel combustion, all of the major components exist at industrial scale, but their integration into a combustion process has not been demonstrated at anything larger than laboratory scale. Experience suggests that there is no significant difference from air combustion; however, there is yet to be a pilot-scale integration of all the major components. A key concern with the oxy-fuel process is the high energy demand for air separation in order to provide the necessary oxygen stream. Oxy-fuel enables capture of $CO_2$ by direct compression of the flue gas without further chemical capture or separation; however, the "purity" of the gas (in terms of $SO_X$ and $NO_X$ contaminants) could be a limiting factor if $CO_2$ sequestration standards are limited to a very clean gas. The oxy-fuel process also has the capability to be retrofitted onto existing power plants, but may have limited application in this area due to the high parasitic energy penalty of the air separation process. Nevertheless, the process has considerable potential for new installations.

Research and development necessary to advance oxy-fuel is focused on reducing the energy demand of the air separation unit. Further work on providing integrated designs, with a study of the affects of flue gas concentrations of $SO_X$ and $NO_X$ on downstream components in the compression, transport and storage chain, is also critical. Finally, thorough evaluation of the costs, benefits and limitations as a retrofit technology is necessary.

## $CO_2$ Transport and Storage

In emphasising $CO_2$ transport and storage, the CIAB notes that, while fuel combustion efficiency, equipment performance and $CO_2$ capture technologies all aim to reduce $CO_2$ emissions, for CCS to be successful, the development effort must provide for efficient transport and long-term storage of $CO_2$ away from the atmosphere. Proposals exist to store $CO_2$ in saline formations, depleted oil and gas fields, deep coal seams and in shale and basalt formations. While there is experience with transport and storage at some locations, mainly associated with enhanced oil recovery (EOR) and processing of natural gas, much effort is needed to optimise site selection for large-scale storage and enhance confidence in storage security. Research needs include: detailed geological assessments of prospective sites, improved understanding and forecasting of $CO_2$ dispersion in geological media to determine permanence and security of storage, and accelerated studies of the technologies that might be used for long-term measurement, monitoring and verification of $CO_2$ storage sites.

In addition to these research requirements, a concurrent effort to develop balanced regulatory frameworks for $CO_2$ storage and monitoring are a critical part of a successful CCS programme. This should include the development of viable options for national and international standards covering the selection, operation and monitoring of $CO_2$ storage sites.

# COMMERCIAL AND POLICY DRIVERS FOR CLEAN COAL TECHNOLOGIES

## Overview and CIAB members' discussion

**Key Messages:**

- Industry experience in developing technologies to reduce a range of pollutant emissions from coal-fired plants provides confidence in the potential to achieve future $CO_2$ emission reductions using CCS, if appropriate policy and commercial drivers are employed.
- In order to achieve significant and widespread $CO_2$ emission reductions through CCS within the time frames established by recent major reports (*e.g. The Stern Review* and reports of the IPCC), wide-ranging, technological improvements need to be made incrementally and soon.
- Significant investment support, reliable legal frameworks and institutional change are necessary to accelerate the deployment of new CCS technologies.

To achieve the ambitious GHG emission reduction targets and timing called for by the IPCC and others, wide-ranging, technological improvements need to be made incrementally and soon, including in energy efficiency, in fossil fuel production, in fuel combustion, and in $CO_2$ capture and storage. There is no "silver bullet" to achieve the quantum leap implied by these ambitious objectives. Successful GHG emission abatement requires the application of a broad variety of technologies in the developed and the developing world.

Of these, the capture and geological storage of $CO_2$ from coal- and other fossil fuel-based power and industrial plants is among the most important in terms of potential to abate future emissions. The CIAB agrees with the conclusion of the MIT study, *"… (an) important premise is that coal will continue to play a large and indispensable role in a greenhouse gas constrained world. Indeed, the challenge for governments and industry is to find a path that mitigates carbon emissions yet continues to utilize coal to meet urgent energy needs, especially in developing economies."* (MIT, 2007, p. ix)

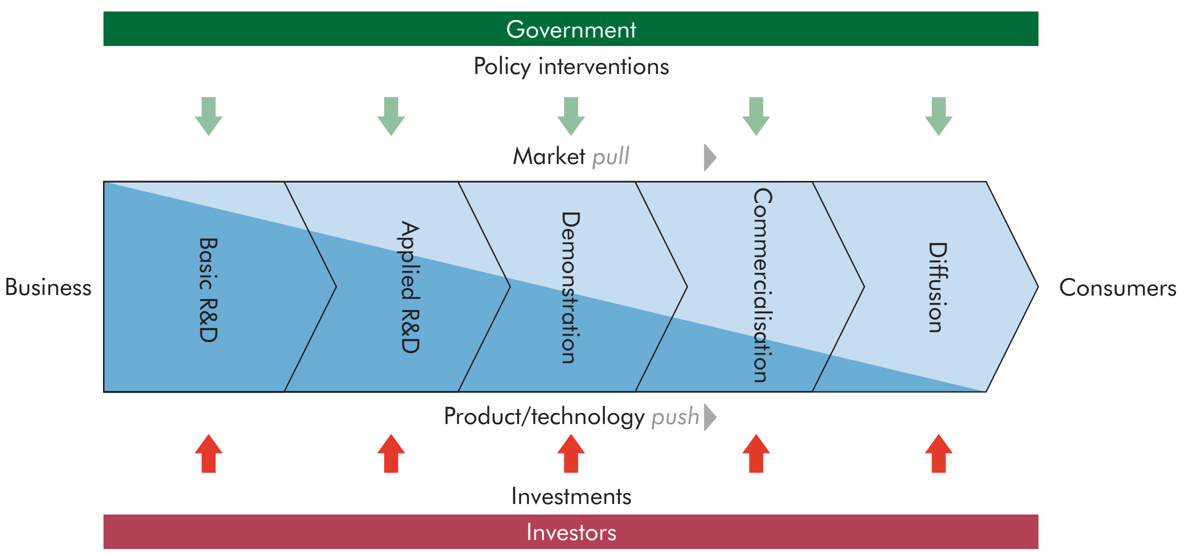
However, for various reasons – including the costs of CCS development and deployment, and the absence of supporting mechanisms and markets – this challenge will not be met without prompt and significant government intervention and leadership in a range of areas – financial, legal and political. Financing R&D

and initial CCS demonstration projects must involve a step increase over current levels of R,D&D spending. Furthermore, in order to accelerate the deployment of new technologies, significant investment support and institutional change is necessary.

The process is significantly more complex than a linear progression from R&D to demonstration, commercialisation, market accumulation and wide-scale diffusion. Experts on technological innovation have noted the importance of feedback in the process and of the links between technological and institutional change (Grubb, 2004). Figure 11 shows the stages of innovation and the roles of individual actors. Linkages between these stages allow learning by doing, learning by using and learning by interacting, all of which help innovators move along the experience curve. Analysis of the experience curves for energy technologies has shown that, in the early stages of development, the unit costs fall by 10-20% with each doubling in cumulative production.

The OECD, in a study of empirical, analytical and policy work covering twenty-four countries, found that differences in size and level of development among countries affected their innovation capacity (OECD, 1999). The study also showed that differences in institutional setup meant that the respective roles of the main actors in the innovation process (businesses, public and private research organisations, and government and other public bodies) often varied from country to country.

## Figure 11. Roles of innovation-chain actors




- The innovation process involves the development and deployment of new technologies, products and services by business in order to meet the needs of consumers. To achieve this, funding is required from a variety of investors, such as insurance companies, banks, private equity houses and angel investors.
- In the early stages of the market, take-up is largely driven by the product/technology "push". As consumer awareness builds, the rate of deployment is accelerated by market "pull" as consumer demand grows.
- Government can make various policy interventions at various stages of the innovation chain to overcome barriers to the development of various technologies, products and services.

Source: Carbon Trust, 2003.

Nevertheless, the OECD study identified several broad trends that create the conditions for successful innovation:

- Innovation increasingly relies on effective interaction between the science base and the business sector;
- More competitive markets and the accelerating pace of scientific and technological change force firms to innovate more;

- Networking and collaboration among firms are now more important than in the past and increasingly involve knowledge-intensive services;
- Small- and medium-sized enterprises (SMEs), especially new technology-based firms, have a more important role in the development and diffusion of new technologies; and,
- The globalisation of economies is making countries' innovation systems more interdependent.

These trends have characterised the ongoing effort to invent and commercialise "conventional" low-emission coal utilisation technologies and processes; the goal of achieving significant GHG emission reductions is simply a continuation of CCT innovation, albeit more urgent and more challenging.

The success over the past half century in reducing emissions of particulates, $SO_2$, $NO_X$ and mercury from coal-fired plants with conventional CCTs provides a firm pathway towards reducing emissions of $CO_2$ from fossil-fired plants. Conventional pollutant emissions were viewed as grave threats to environmental quality, notably in the USA, Europe and Japan, but over the past fifty years, successful application of new technologies has controlled these emissions – even as coal-based generation has continued to expand. While these technologies have yet to be widely adopted in many developing countries, CCT deployment promises to reduce environmental impacts while retaining coal as a commercially viable option to fuel economic growth and alleviate poverty. Factors ranging from government-funded R&D, mandatory regulations, investment support, and flexible emissions trading schemes interact to bring about the control of these emissions; furthermore, they can encourage deployment of emission reduction technologies and policies in the developing world.

The CIAB has reviewed the list of technologies currently being developed in Europe, Japan, Australia and the USA and concludes that low-carbon and near-zero emission power plants are reasonably on track to be developed, refined and deployed. The introduction of urgency by the IPCC and others to achieve significant emission reductions by 2050, rather than just slowing the rate of emissions, means that efforts must be accelerated. In order for CCS technologies to be implemented successfully within the next four decades, the process used to improve coal's environmental performance and maintain its commercial viability to date needs to be intensified. Elements of this process include:

- Establishing a clear, balanced legal framework for $CO_2$ transport and storage;
- Promoting public understanding and acceptance of $CO_2$ capture and storage (CCS);
- Funding CCS research, development and deployment;
- Establishing tax incentives and loan guarantees for CCS R,D&D and commercial projects;
- Supporting commercial opportunities for use of $CO_2$ for enhanced oil recovery (EOR) and enhanced coalbed methane production as a means of developing CCS technology and infrastructure;
- Promoting commercial opportunities in transport fuel and chemical production from coal as a means of developing CCS technology and infrastructure;
- Supporting market-based responses, such as GHG cap-and-trade systems, to speed the ultimate commercialisation of CCS;
- Encouraging mandatory price supports and feed-in tariffs based on the avoided emissions from systems with CCS; and,
- Promoting participation of emerging economies in CCS development and deployment.

These elements were discussed by CIAB members at their Plenary meeting in November 2007. At the meeting, members:

- Emphasised the need for government support in the early stages of the process;
- Reinforced the need for capital support, and for governments to assist in funding, particularly against the current backdrop of escalating capital costs;

- Supported cap-and-trade systems in the later stages of the CCS development and commercialisation process;
- Saw participation of the emerging economies as crucial, with loan subsidies through the World Bank being a possible means of encouraging their involvement; and,
- Specifically requested that the IEA take all possible steps to ensure that a methodology is developed and agreed for CCS to become eligible for Clean Development Mechanism credits under the Kyoto Protocol.

Recognising the need to reconcile greenhouse gas emission reductions with growing energy demand and security of supply, members also highlighted some of the wider CCS development issues facing industry and governments. CCS needs to be developed and deployed as soon as practicable, but also needs to be sustainable. The energy demand of CCS operation reduces power station output and capacity, thus necessitating additional coal production and new mine development. For this reason, there will be a continuing need to focus on reducing the efficiency penalty of CCS and to promote efficiency improvements along the whole value chain, including through the deployment of new, efficient, electricity-generating technologies. Near-term opportunities exist for CCS deployment and are the focus of G8 activities led by the IEA and CSLF (G8, 2005).

The workshop *"$CO_2$ Capture & Storage - international progress and future prospects"* that followed the Plenary meeting, co-hosted by the CIAB, the Royal Society, and the Royal Academy of Engineering, concluded that CCS was a pivotal climate change mitigation technology. Against a backdrop of rising global energy demand and a continued reliance on fossil fuels for the foreseeable future, illustrated by future energy scenarios from the IEA *World Energy Outlook 2007*, the need to address climate change creates an additional challenge to future energy security. The necessary deep cuts in $CO_2$ emissions, as indicated by the IPCC and increasingly reflected in government policies, mean that urgent progress is needed on low-carbon technologies for power generation and other industrial processes, including CCS for coal- and natural gas-fired power plants. The significant progress reported at the workshop on the legal and regulatory frameworks to enable CCS is encouraging, and includes the steps now being taken by the European Commission to incorporate CCS in the EU Emissions Trading Scheme.

However, to promote its rapid demonstration and deployment alongside other technologies, governments must also take positive steps to reduce investment risk. Many projects with the potential to demonstrate the viability of CCS for power generation were presented, with the common conclusion that these now require greater policy and financial support. Indeed, the political desire to address climate change must be turned into actions that lead to public understanding and support for the necessary and substantial costs involved. Assessments have shown that CCS could reduce these costs, but this demands commercial-scale demonstration of the various CCS technology options to build the confidence amongst investors and the public that would enable their widespread deployment, including in the world's rapidly developing economies such as China and India. Many participants referred to the important role that the Kyoto Protocol's Clean Development Mechanism could play here, but only if CCS is accepted as an eligible activity for tradable credits.

A straw poll at the workshop revealed that the majority of those present believed that non-commercial CCS could be demonstrated at large scale by 2014, with commercial operation achieved between 2016 and 2020. These remain challenging targets that can only be achieved if the urgency expressed by some spreads to become a demand of the majority. Experienced practitioners warned that the remaining technical, economic, policy, regulatory and legal issues must be addressed simultaneously and with determination. In particular, proving the safe storage potential for $CO_2$ is as urgent as demonstrating the capture technologies and potentially as challenging as developing major oil and gas fields.

Failure to succeed with CCS would force painful and perhaps unmanageable policy choices between pursuing energy security and addressing climate change. In this respect, CCS emerges as an indispensable part of the solution.

The remainder of this section addresses each of the commercial and policy drivers in more detail.

## Establishing a clear, balanced legal framework for $CO_2$ transport and storage

**Key Messages:**

- Lack of a clear regulatory and monitoring framework for $CO_2$ transport and storage could significantly slow, or even stop, a global CCS initiative.
- A move to large-scale CCS requires a set of internationally and nationally consistent principles to provide a framework for CCS activities in multiple jurisdictions.
- Ownership of stored $CO_2$, the long-term responsibility for storage sites and public access to information regarding $CO_2$ storage are major issues requiring a clear legal and regulatory framework.
- There is a role for an international agency to provide a repository for rules and principles developed by national and other jurisdictions, to promote inter-party discussions and dissemination of knowledge, and to formulate regional, national and international legal templates for the operation of CCS systems.

$CO_2$ capture, transport and storage is already occurring at a few locations, and rules governing processing, transport, injection and storage site monitoring have evolved, consistent with the national, regional, local and industrial norms of where it is occurring. Thus, the legal framework governing $CO_2$ transport and storage is at different stages of development in different places, and there is no paramount national or international model available for timely application (IEA, 2007f). Lack of a clear regulatory and monitoring framework could significantly slow, or even stop a global CCS initiative.

A move to the widespread deployment of CCS in order to achieve significant GHG emission reductions requires the development of a set of internationally and nationally consistent principles to provide a framework for CCS activities in multiple jurisdictions. While most international jurisdictions recognise three stages of CCS (capture, transport and injection), some national models include a fourth stage in the life cycle – the post-closure phase, which incorporates storage, decommissioning and long-term responsibilities. A major issue that needs to be resolved is the legal and regulatory structure that addresses ownership of stored $CO_2$, responsibility for geological storage sites, and public access to information on storage sites and risks. The CIAB supports a robust legal structure which addresses trans-generational issues and ensures public trust.

The absence of a regulatory framework that is clear and transparent to the public will destroy trust in the entire process. However, a fine balance is necessary as the legal structures governing CCS practices must protect the public interest without disincentivising industrial applications. For example, efforts to over-regulate storage of $CO_2$, whose emission into the environment from natural sources is common, would risk crippling the entire process, while moves to classify $CO_2$ as a hazardous waste or pollutant would ignore the ubiquitous presence of the gas in nature and severely deter application of CCS.

The CIAB supports actions by the Carbon Sequestration Leadership Forum and international agencies, like the IEA and the United Nations, to initiate, accelerate and co-ordinate the development of a balanced legal framework. A centralised, multi-national repository of the individual rules and principles developed by national and other jurisdictions and by industry needs to be created and maintained. Furthermore, inter-party discussions and diffusion of knowledge about solutions and methodologies, need to be stimulated by international conferences, publications and other communications. Finally, regional, national and international legal templates need to be formulated by a recognised multi-national body to serve as a starting point for the operation of CCS systems as they proliferate.

## Promoting public understanding and acceptance of $CO_2$ capture and storage (CCS)

**Key Messages:**

- The public does not have a good understanding of CCS and is not well informed on CCS issues.
- In democratic nations, public acceptance of CCS will be critical to development of the policy framework that is necessary to enable CCS deployment.
- Outreach programmes to improve public understanding of CCS and public endorsement of CCS by public authorities, including political leaders, policy makers and NGOs, will be essential to public acceptance.
- Much more needs to be done by credible agencies to raise public awareness and understanding of CCS.

Although the IPCC has noted the difficulty of gaining public acceptance for CCS because of its relatively technical and "remote" nature, few studies have been conducted about public perception (IPCC, 2005). These suggest that the public is not well informed on the issue. Nevertheless, a fledgling start that includes regional public outreach programmes, media presentations and support for CCS by environmental groups is occurring. While surveys show that public awareness of global climate change is rising, there is, at best, fleeting awareness that addressing the issue requires imposition of regulatory mechanisms that may result in steep price increases for electricity and other forms of energy. These same studies suggest that transparency and fair burden sharing are considered important by respondents and should feature in any mitigation plan. Many stakeholders have been brought into the process wherever public outreach is in progress, but the objective of cutting GHG emissions significantly by 2050 is not one that can be presented by industry alone, nor by informal consortia of government agencies and non-governmental organisations.

The CIAB believes that public outreach programmes and public endorsements of CCS technology by politicians and policymakers in countries considering undertaking CCS are essential. National governments and international agencies must directly address concerns about costs, regulation, monitoring, safety and verification that are foremost in the public's mind. While the IEA Greenhouse Gas R&D Programme has supported basic safety principles by analyzing and publishing findings on instances of natural releases of $CO_2$, a more intensive and broader review is required to demonstrate the safety of $CO_2$ storage in stable sedimentary basins (IEA GHG, 2006a).

Much more needs to be done to raise public awareness. Policy makers and opinion leaders must be more forthcoming in explaining to their constituencies the significance of CCS technology and its potential ability to contain the much-feared affects of global climate change. It will take those who have credibility on this issue, including government safety and environmental offices, international environmental groups and international bodies, like the IPCC, the UNFCCC and the IEA, to co-ordinate a mutually supportive information dissemination effort.

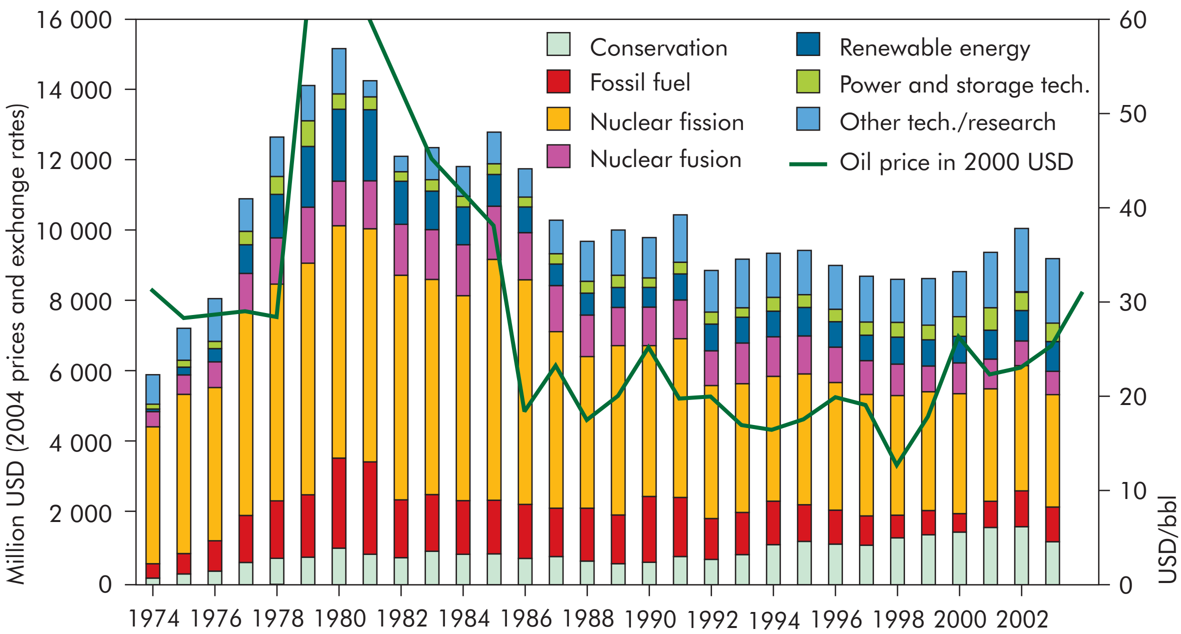
## Funding CCS research, development and deployment

**Key Messages:**

- Recent government-industry partnership initiatives have been established for the purpose of advancing development and deployment of CCS technologies.

- Given the need for significant and widespread CCS deployment within the coming decades, a massive increase in energy R&D funding is required, reversing the decline in public and industry spending over several decades.
- The potential for leakage of new technological development to competitors is a disincentive for private sector investment in basic energy R&D.
- A significantly greater level of funding is needed to stimulate CCS demonstration projects in the next decade that lead to commercial operation of CCS power stations in the 2020s.

**Figure 12. R&D expenditure in IEA countries (left axis) and oil price (right axis) 1974-2003**




Source: OECD, 2006.

The CIAB supports the view that to introduce "near-zero" emission technologies will require massive R&D expenditure – primarily by governments in developed countries. A review of IEA data shows that while public budgets for R&D have increased in past decades, expenditure on energy R&D has declined, and the public sector decline has not been compensated for by an increase in private sector expenditure. Figure 12, derived from IEA data, suggests that energy R&D expenditures correlate with oil prices. The end of high oil prices in the second half of the 1980s and throughout the 1990s led to a significant decline in R&D expenditure on energy technologies. The period from 1980 to 2003 has seen funding decline in major R&D programme areas, including renewables, fossil fuels and nuclear (Table 3). Only energy conservation R&D funding has seen an increase. Total funding for fossil fuel R&D programmes declined to approximately USD 1 billion in 2004. $CO_2$ capture and storage technologies accounted for only 1.1% of the share of IEA member countries' total public R&D expenditure in 2004, with other aspects of fossil fuels, including generation efficiency, accounting for a further 10%. Furthermore, since there is a significant disincentive for private sector investment in basic R&D, because of the speed of leakage of new technological developments to competitors, many businesses are reluctant to invest in leading-edge energy technology R&D. A survey of energy R&D expenditure by industry in OECD countries reveals that this has been in steady decline since 1990 (OECD, 2006).

**Table 3. Aggregate percentage change in major public sector energy R&D programme areas of eleven IEA member countries**

| | 1980-1990 | | 1990-2003 | |
|---|---|---|---|---|
| | All | w/o US, Japan | All | w/o US, Japan |
| Conservation | -20% | -42% | +78% | -36% |
| Fossil | -78% | -77% | -68% | -64% |
| Renewable | -75% | -56% | -5% | -14% |
| Nuclear | -91% | -83% | -88% | -63% |
| **Aggregate** | **-65%** | **-80%** | **-53%** | **-65%** |

Source: Runci, 2005.

Governments will need to play a much greater role in funding R&D initiatives. In regard to CCS technologies, the role is not only to fill in knowledge gaps, but also to provide financing for early demonstration projects. Governments also play a crucial role in knowledge transfer, through conferences and encouraging government-business collaboration.

The CIAB finds it encouraging that governments are playing a role in funding and promoting government-private partnerships at the national and international level, in spite of the long-term decline of financial support for energy R&D. Though the effort is under funded, the journey down the path towards reducing GHG emissions from coal use is underway. The European Union, individual EU member countries, the USA, Australia, Canada and Japan currently support research efforts for $CO_2$ capture, transport, storage, monitoring and verification. Governments have been joined in this effort by numerous large and small businesses from the coal supply and utilisation chain which have provided funding and technical support. However, a significantly greater level of funding is needed to stimulate the many demonstration projects needed in the next decade. A 2007 study by the Australian Business and Climate Group strongly endorses emissions trading, but stresses the need for public-private partnerships and large-scale public support for R&D to accelerate deployment of CCS (ABCG, 2007). Another study of CCS potential by the Massachusetts Institute of Technology recommended US government spending of USD 460 million per year for the next five years to cover necessary CCS analysis, research and development needs (MIT, 2007, p.104).

## Establishing tax incentives and loan guarantees for CCS R,D&D and commercial projects

**Key Messages:**

- Loan guarantees have a significant, positive effect on the willingness of companies to invest in taking pilot technologies to commercial scale.
- Tax incentives can encourage industry to invest in R&D and to accelerate the deployment of new technologies.

Loan guarantees and tax incentives have a long history of use in Australia, EU countries and the USA to encourage the introduction of clean coal and other "green" technologies. In developed economies, the loan guarantees encourage private capital markets to finance projects made "risky" by volatile prices, use of new technology and difficulties associated with scaling pilot projects to commercial size. An April 2007 report by the US National Energy Technology Laboratory stresses that loan guarantees have the largest impact on overall plant economics and significantly increase returns on investment (NETL, 2007). The guarantees allow higher debt-to-equity ratios and thus reduce up-front capital requirements, whilst providing projects with strong positive cash flows because of lower interest payments. They also reduce the risk to equity investors by limiting their financial exposure.

Tax incentives – provided as credits and accelerated depreciation – are particularly advantageous at the deployment stage, because they act to reduce finance costs. Since significant risk, and thus high discount rates, often apply to new technologies, reducing the cost of capital is essential during the deployment phase. Tax mechanisms have other advantages. They can be applied to a wide range of new energy options – thus ensuring that government does not disrupt market forces by favouring one energy source over another. Properly structured, tax mechanisms such as investment tax credits can spur new investment that otherwise would not have occurred. When this approach is applied, any tax that is collected – even if at a lower rate – can add to a government's overall tax revenues. Tax measures, like accelerated depreciation, can fund the deployment of higher performance technology to replace existing technology[15]. At the research and development stage, tax concessions can offset the reluctance of the private sector to invest in expensive research efforts. Companies that increase their R&D expenditure above a base level can gain significant tax deductions to protect income from their profitable activities. The CIAB notes that successful tax incentive and loan guarantee programmes have been mainly associated with developed economies where the financial and tax structures are in place for application and monitoring of such complex and comprehensive programmes.

## Supporting commercial opportunities for use of $CO_2$ for enhanced oil recovery (EOR) and enhanced coalbed methane production as a means of developing CCS technology and infrastructure

**Key Messages:**

- Use of $CO_2$ for enhanced oil recovery (EOR) and enhanced coalbed methane production provides opportunities for early CCS deployment.
- The use of $CO_2$ for EOR is a very important technological driver for CCS because it provides a revenue stream to defray the cost of developing $CO_2$ transport and injection infrastructure.
- Expansion of $CO_2$ use for EOR, coalbed methane development, and similar applications can expand $CO_2$ markets and hence demand for $CO_2$ captured from fossil fuel facilities, thus providing economic incentives for early applications.
- EOR provides a vehicle for promoting CCS while also providing additional opportunities for research and learning.
- Governments and international agencies should support EOR and enhanced coalbed methane as "bridging" technologies that will aid development of CCS.

The use of $CO_2$ for enhanced oil recovery (EOR) is a key technological driver for CCS since it provides an opportunity to earn revenues from the sale of $CO_2$ to cover the additional cost of carbon dioxide capture and transport.

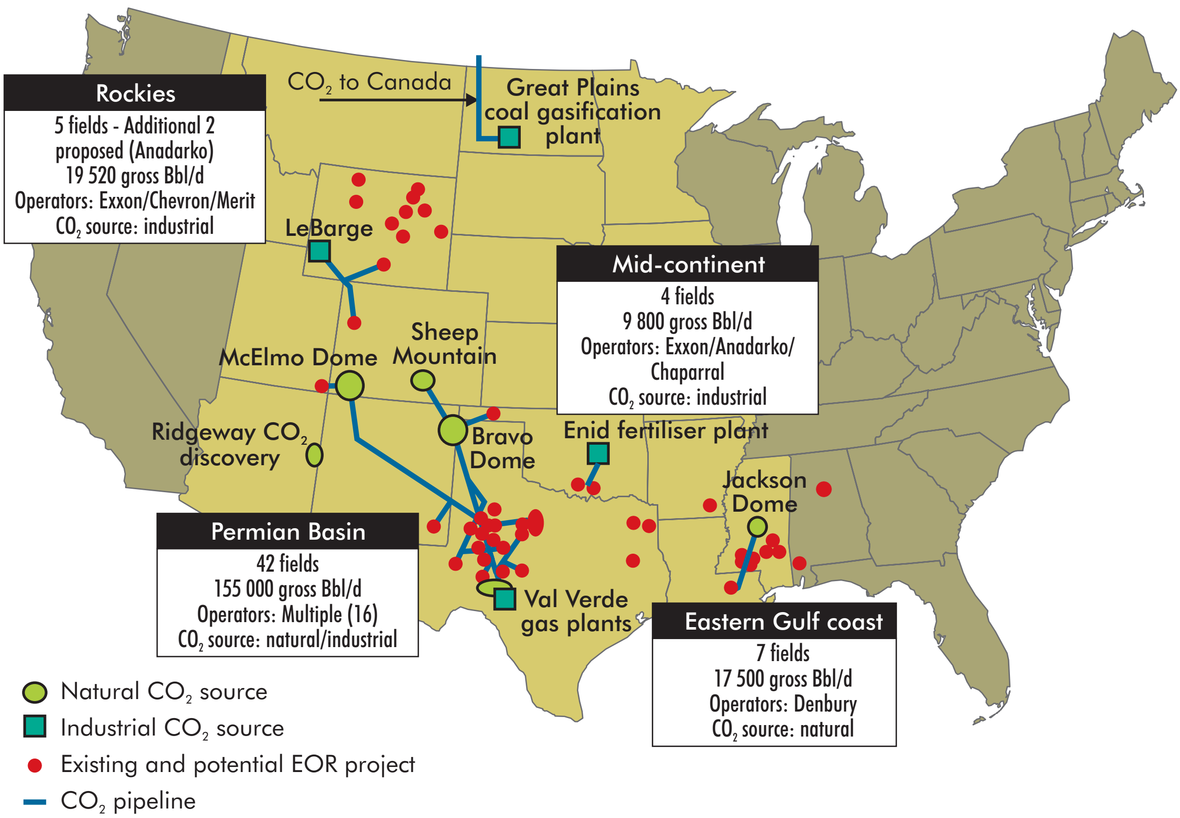
There are two value-added uses for $CO_2$ already established in the oil and gas industry: enhanced oil recovery through $CO_2$ injection and enhanced gas recovery. EOR is more common than enhanced gas recovery because the recovery rate from a natural gas reservoir diminishes with the eventual breakthrough of $CO_2$ into

15 In Germany, after reunification, tax measures, particularly accelerated depreciation, played a major role in funding the EUR multi-billion investments which completely renewed the energy sector in the territory of the former DDR, resulting in the closure of old inefficient power plants. These were then either retrofitted or, in many instances, replaced by the world's most modern and efficient brown coal-fired units.

the produced natural gas, requiring the $CO_2$ to be separated and re-injected into the reservoir. Two other gas recovery processes have some potential: injection of $CO_2$ into coal seams to improve the production of coalbed methane; and, linking $CO_2$ injection into deep coal seams with in-situ coal gasification[16]. Both processes are currently at the research and evaluation stage.

The North American oil industry has over thirty years experience with $CO_2$ injection at EOR projects. Figure 13 provides an overview of the current $CO_2$ EOR projects operating in the USA and shows how these have led to the creation of a $CO_2$ infrastructure. Many projects use $CO_2$ from natural sources, but there are $CO_2$ EOR projects which use anthropogenic $CO_2$. A notable example is the Great Plains Coal Gasification Plant in North Dakota which ships dense-phase $CO_2$ to Saskatchewan for use by EnCana for EOR in the Weyburn oil field.

**Figure 13. Operating $CO_2$ enhanced oil recovery (EOR) projects in the USA**




Source: Denbury Resources, 2007.

Coalbed methane production is a mature industry in the USA, although enhanced coalbed methane recovery through $CO_2$ injection is not currently practiced on a wide scale. Because $CO_2$ is readily adsorbed on internal coal surfaces, injection of $CO_2$ into these seams displaces methane and can enhance its recovery. Results of a five-year commercial pilot programme in the San Juan Basin of Colorado and New Mexico, USA, indicated that such operations cause $CO_2$ to be stored efficiently and that substantial incremental recovery of coalbed methane is possible at reasonable cost (Reeves, 2005).

16 For this technology, see research publications of the Carbon Management Program, Energy and Environment Directorate, Lawrence Livermore National Laboratory at http://eed.llnl.gov/co2/.

The CIAB notes that there are challenges to the increased use of $CO_2$ for EOR because not every oil reservoir is appropriate for this tertiary oil recovery technique. EOR projects have high upfront capital investment costs with long payouts, making them more attractive in periods of high oil prices. Furthermore, EOR is a viable approach in only those locations where oil production is, or has been, present. However, EOR raises the prospect of covering the cost of developing $CO_2$ transport and injection infrastructure. Often there are saline aquifers above and below producing strata in oil fields where additional $CO_2$ can be stored. The Weyburn project, which involved the construction of a new 204-mile (326-kilometre) twelve-inch pipeline from the Great Plains Coal Gasification Plant to the Weyburn oil field in Saskatchewan, was financed commercially on the basis of the reported USD 30/tonne price for the $CO_2$, paid by the EOR project developer. The reported $CO_2$ price in the Permian Basin in Texas, where $CO_2$ EOR production has a long history, is reported to be about USD 50/tonne.

Wider application of EOR is limited by the availability and commodity cost of $CO_2$. The IEA Greenhouse Gas R&D Programme (IEA GHG) has noted that once carbon credits are awarded for the $CO_2$ stored during EOR, then this added economic incentive would allow EOR implementation on a far wider scale (IEA GHG, 2006b). The CIAB supports the IEA GHG's conclusion that EOR has potential as an early driver for $CO_2$ storage before a more robust economic and regulatory structure is in place. Furthermore, the CIAB agrees that technologies enabling $CO_2$ monitoring underground should be positively supported by policy and regulatory measures. The point is that EOR provides a vehicle for promoting $CO_2$ capture, transport and storage while providing additional research opportunities to advance along the learning curve. Government can promote the application of EOR by identifying sites where it has potential, developing a framework for its application and providing incentives for the oil sector to apply it. Governments and multi-national agencies need to support utilisation of these "bridging" processes that have the potential to defray the increased cost of CCS deployment. Such support may take the form of expanding geological research and inventories, and supporting investment by reducing financial and regulatory risk. Finally, the use of EOR as an early driver for $CO_2$ storage can be applied in both developed and developing countries, wherever depleted or depleting oil fields exist.

## Promoting commercial opportunities in transport fuel and chemical production from coal as a means of developing CCS technology and infrastructure

**Key Messages:**

- Both the level of political support and today's high oil prices make it possible for coal-to-liquids (CTL) to gain public acceptance and to become commercially viable.
- Because carbon dioxide can be captured at a lower cost per tonne from CTL and coal-to-hydrogen (CTH) processes than from existing coal-fired power generation plants retrofitted with post-combustion capture, CTL and CTH production provides opportunities to develop CCS technology and infrastructure. CTH may ultimately provide an opportunity to substantially reduce $CO_2$ emissions from the transport sector.
- Processes that create high-value products can accelerate CCS deployment by generating cash flow to cover its deployment cost.

Recent concerns about energy security have increased support for the development of new coal-to-liquids (CTL) projects in several countries. Although the technology is mature, and scores of CTL projects have been proposed throughout the world, these projects are only viable at oil prices of around USD 40/bbl or above. Without CCS their $CO_2$ "footprint" is at least 150-175% higher than that of conventional gasoline/diesel production. Despite strong political support for CTL in several countries, projects face opposition from environmentalists and, without CCS, run counter to the objective of reducing GHG emissions. This is also true of other "alternative" liquid fuels like gas-to-liquids (GTL), oil shale and oil sands projects; the IPCC, in its May 2007 report, stressed that all unconventional petroleum or synthetic petroleum projects should be developed in combination with CCS (IPCC, 2007). The CIAB notes that this places an extra burden on CTL because the technology has not yet been deployed with CCS, but both the level of political support and today's high oil prices make it possible for such projects to gain public acceptance and to become commercially viable. The CIAB supports deployment of CTL facilities with CCS since they have the potential to bear the higher cost of CCS and establish a $CO_2$ transport and storage infrastructure that can subsequently be applied to power generation facilities.

A further driver for CCS deployment is the ability of coal gasification to produce a clean fuel for the residential and transport markets. The transport sector presents a significant obstacle to $CO_2$ emission reductions. However, in the future, hydrogen has the potential to become a major clean transport fuel. At present, there are few economic alternatives to completely eliminate $CO_2$ emissions from mobile sources. Coal-based hydrogen production with CCS allows for large-scale $CO_2$ removal and storage while producing a motor fuel that has no carbon dioxide emissions. Studies in at least two countries concluded that coal gasification is the lowest-cost source for hydrogen (EPRI, 2006). Furthermore, since stationary fuel cells are also a potential clean energy provider for the residential and small commercial sectors in the future, hydrogen from coal gasification could be used to displace $CO_2$ emissions from the numerous small sources in these sectors.

In addition to the conversion of coal into transport fuels, efforts to expand and deploy coal-to-chemicals industries in several countries offer an opportunity to combine coal gasification with CCS to produce high-value products that can bear the early cost of the emission control technologies. As a petrochemical feedstock, the syngas from a coal gasifier can be used for coal-to-methanol or coal-to-dimethyl ether and other products. As with CTL, encouragement of such processes with CCS has potential to accelerate the expansion of the infrastructure necessary to support more widespread application of CCS. The CIAB endorses support of processes that create high-value products because they can accelerate CCS deployment by generating cash flow to cover costs, and promote research and demonstration activities. Such support might include expanding geological inventories, research into monitoring techniques, and demonstration of injection and monitoring systems. Investment in large-scale projects could be promoted by reducing financial and regulatory risk with favourable tax and loan treatment.

## Supporting market-based responses, such as GHG cap-and-trade systems, to speed the ultimate commercialisation of CCS

**Key Messages:**

- Experience with $SO_2$ and NOx cap-and-trade systems supports the view that they increase flexibility and reduce the cost of emission reductions.
- The Kyoto Protocol's Clean Development Mechanism could provide new opportunities to support investments that lead to technology transfer to the developing world.
- Given the limits to fuel switching, the CIAB believes that cap-and-trade schemes will prove most effective when CCS-based technology solutions are widely available.

Cap-and-trade systems have been used to limit emissions of several pollutants in North America and carbon dioxide in Europe. Decisions taken by governments in Australia and New Zealand mean that those countries will have GHG emission trading schemes in place for power plants by 2010/11. Cap-and-trade systems utilise market forces to provide economic incentives for emission reductions, a mechanism that differs in a fundamental manner from traditional "command and control" regulatory approaches, such as those that apply inflexible limits to emissions from individual sources. The CIAB agrees with supporters of cap-and-trade systems, who argue that markets allow greater flexibility and reduce emissions at lower costs due to greater efficiency in the identification of emission reduction opportunities. Experience with $SO_2$ and $NO_X$ reductions in North America supports the argument, while the European experiment with $CO_2$ cap-and-trade is, as yet, in its early stages.

The basic design of cap-and-trade systems involves the allocation of emission rights in a variety of ways, including grandfathering, technology bench-marking or auctioning. The rights owners are then free to emit in quantities up to the limit implied by the number of rights held. Generally, the initial allocation of rights will be less than current emissions; thus, emitters must reduce their emissions by some means – usually technological or by fuel switching – or cover their emissions by obtaining rights from the market. Given the limits to fuel switching, the CIAB believes that cap-and-trade schemes will prove most effective in the later stages of the CCS development and commercialisation process, when technology solutions are widely available. Use of cap-and-trade with power generation has the best record of success; power generators are able to pass on the higher cost of emission rights in the price of electricity because they are competing in national or regional – rather than global – markets. Stern has observed that the ultimate economic impact of pricing carbon under a cap-and-trade system is not that different from a carbon tax. Since the ambitious GHG emission reductions proposed by the IPCC and *The Stern Review* demand nearly complete decarbonisation of the electricity sector by 2050, cap-and-trade offers one route towards achieving that objective.

Experience with cap-and-trade systems in both North America and Europe underscores the role of national governments in setting caps, authorising and distributing rights, measuring emissions and maintaining a transparent performance monitoring and accounting system that allows banking of rights. Furthermore, in the case of GHG emission reductions, substantial incentives are needed to transfer CCS technology to the developing world. The Clean Development Mechanism (CDM) and, to a lesser extent, Joint Implementation (JI) under the Kyoto Protocol, in combination with national or international cap-and-trade programmes, offer a pathway towards supporting investments in technology and in the transfer of technologies to the developing world. As with the national effort, multi-national agencies will need to create the monitoring, accounting and authorisation structures for these procedures to function effectively and efficiently.

## Encouraging mandatory price supports and feed-in tariffs based on the avoided emissions from systems with CCS

**Key Messages:**

- Price supports and mandatory feed-in tariffs have been used successfully to support rapid deployment of non-fossil, low-emission energy technologies.
- Use of these approaches for deployment of low-emission technology is highly effective and brings the technologies into the mainstream rapidly.

Price supports and mandatory feed-in tariffs have been used successfully in some IEA member countries to support the rapid deployment of low-emission technologies, like wind and solar, into the electricity generation base, and should also be used for low-emission coal technologies. Because of the ambitious objectives proposed for achieving substantial GHG emission reductions by 2050, the CIAB supports using this approach to stimulate the rapid deployment of CCS. Experience shows that these approaches for the deployment of expensive technologies with "above-market" costs are highly effective and bring the technologies into the mainstream rapidly. The net effect is to create strong incentives for investment in the deployment of new technology. A form of mandatory feed-in – portfolio standards – has been enacted in some countries and could allow development of "critical mass", if applied to CCS.

National governments have a large role to play in designing and mandating this support. It offers a means to use existing market and regulatory structures to achieve GHG emission reductions in the electricity sector with low intervention. The mechanisms can be adjusted to reflect technology maturity and substitute prices as time passes without undue interference to existing price and distribution systems. This approach would most likely work best in developed countries with mature electricity production and distribution infrastructures, and with experience of this approach for other low-emission technologies.

## Promoting participation of emerging economies in CCS development and deployment

**Key Messages:**

- The reliability and cost effectiveness of new, higher-efficiency, electricity generation technologies has not been fully transferred to developing countries.
- Consideration should be given by organisations such as the World Bank to subsidising capital for projects that have environmental benefits going beyond national boundaries, including CCTs and CCS.
- Consideration should be given to making available, at low cost, intellectual property rights to CCS technologies.
- To support CCS deployment in developing countries, CCS should be made eligible for tradable credits under the Kyoto Protocol's Clean Development Mechanism.

The greatest impediment to the application of CCS technology in the developing world, particularly in the rapidly rising economies of Asia, is cost. If one accepts the policy commitment of many national leaders to keep global warming increases below 2°C, mechanisms are needed to strengthen and finance the deployment of a portfolio of clean coal technologies in developing countries. This entails accelerating efforts to improve coal combustion and power plant efficiency through coal washing and upgrading of equipment at existing power plants, as well as promotion of new, high-efficiency power generation technologies and, ultimately, deployment of CCS. In 1998, the CIAB published the results of a survey of the barriers to the greater application of energy-efficient, coal-fired, power generation technologies to meet the growing world-wide demand for electricity. This included a survey of IPP developers in several developing regions to discover why they were primarily using sub-critical pulverised coal technology. The factors cited focused on reliability, technology cost and financing constraints (CIAB, 1998). Thus, while higher-efficiency technologies have been refined and deployed in developed countries, their reliability and economic viability have not led to wide adoption in developing economies. Furthermore, the CIAB notes that approaches like developed countries' export credits, loan subsidies, financial support from the World Bank or other international agencies, and direct technology transfers, which have been used to support modernisation in developing countries, have not gained widespread acceptance to speed the deployment of CCTs and CCS in the developing world. One initiative, proposed by a former national treasury official, is to have the World Bank and regional development banks form *"banks for development and the global environment"*[17]. Their primary mission would

17 *Practical Steps to Climate Control*, Lawrence H. Summers, Charles W. Eliot University Professor at Harvard University, writing in the Financial Times, May 29, 2007.

become the provision of subsidised capital for projects that have environmental benefits going beyond individual national borders. They could provide financing for energy efficiency, renewable energy and low-emission fossil fuel projects.

While developing country involvement in Australian-, US- and EU-supported CCS projects suggests that dissemination of knowledge on CCS technology is underway, the response of the IPPs mentioned above indicates that more knowledge transfer and perhaps on-site demonstration in developing countries may be necessary. Consideration should be given to making available low-cost intellectual property rights to CCS technologies. A model for this transfer may be found in the pharmaceutical industry, which has developed methods, in co-operation with international agencies, for transferring drug patents at lower cost to developing countries. A move by the CDM Executive Board of the UNFCCC in September 2007, to authorise new grid-connected power plants using less GHG-intensive technology to sell certified emission reductions, offers another means to support deployment of CCTs in developing countries and one that could be extended to support CCS.

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# ACKNOWLEDGEMENTS

The CIAB Members wish to thank Associates and others from their companies who contributed to the production of this report under the strong leadership of Mr Deck Slone of Arch Coal Inc.

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9, rue de la Fédération
75739 Paris Cedex 15

Printed in France by the IEA
February 2008